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ARTEMIS: Assessment and Reliability of Transport Emission Models and Inventory Systems – final report

P G Boulter and I S McCrae (Eds)

Assessment and reliability of transport emission models and inventory systems

Final Report

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Assessment and reliability of transport emission models and inventory systems

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This Report, presents the findings of the ARTEMIS research programme and describes the resulting inventory model. It provides a summary of the research investigations undertaken within the ARTEMIS programme, and includes links where appropriate, to interactions with COST Actions and national emission measurement and modelling programmes. The ARTEMIS project commenced in 2000, and had two principal objectives. The first of these was to gain, through a programme of basic research, a better understanding of the causes of the differences in model predictions, and thus to address the uncertainties in emission modelling. The project included a large emission measurement programme, designed to provide a significant extension to the available databases. For road transport, measurements conducted in many laboratories around Europe were used to examine the reasons for variability in the data, and to form the basis of a ‘best practice’ guide for future measurements. The second principal objective was to develop a harmonised methodology for estimating emissions from all transport modes at the national and international levels.</td></tr>
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PART A: INTRODUCTION

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A1 ARTEMIS in context

Air pollution has been one of Europe's main political concerns since the 1970s, and European Union (EU) policy aims to develop and implement appropriate instruments to improve air quality. Furthermore, there is strong evidence that emissions of greenhouse gases from the burning fossil fuels are linked to a rise in global temperature, and climate change is expected to have a considerable impact on the environment, human health and society. The calculation of emissions to the atmosphere has therefore gained institutional importance in the European Community, particularly with the development of Clean Air for Europe (CAFE) programme. CAFE is a programme of technical analysis and policy development that underpins the development of the Thematic Strategy on Air Pollution under the Sixth Environmental Action Programme. Therefore CAFÉ, in combination with the European Climate Change Programme (ECCP), are significant drivers for the improvement in transport emission inventories and models and represent important project stakeholders.

Emissions from transport are an important - and often dominant - source of air pollution, with direct and indirect detrimental impacts on human health, ecosystems and cultural heritage. Transport also contributes significantly to emissions of greenhouse gases and energy use. EU policy objectives therefore include the control of emissions from mobile sources, improvements in fuel quality, and the promotion of environmental protection in the transport and energy sectors.

In order to assess the present and future state of emissions from transport, and to evaluate different policies for reducing emissions, it is necessary to understand pollution sources and to quantify the releases of pollutants to the atmosphere at different levels of spatial resolution (local, regional, national, international). This requires the development and application of emission models. Accuracy, reliability, consistency and credibility are pre-requisites of emission estimates. However, comparisons between the results from different emission models and different national inventories have highlighted substantial differences. This has led to some doubts about the credibility of the underlying data and methodologies, and consequently the potential to misinform decision makers and stakeholders. The issue of data and model uncertainties remains an important area for improvement.

The European Commission 5th Framework project ARTEMIS (Assessment and Reliability of Transport Emission Modelling and Inventory Systems) was conceived to address the need to develop a harmonised emission model for road, rail, air and ship transport, and to provide consistent emission estimates at the national, international and regional levels. This should help to minimise methodological disputes, and to facilitate more efficient decision-making concerning air quality improvement and the welfare of citizens. Moreover, because transport in Europe consumes enormous quantities of resources, optimised and more accurate information ought to lead to economic and social improvements.

This Report, which presents the findings of the ARTEMIS research programme and describes the resulting inventory model, is one of two final outputs from the project - the other being the model itself. The remainder of this introductory Part of the Report contains a discussion of the political frameworks within which emission inventories are compiled, including legislation, international activities and reporting obligations, a discussion of existing emission factors and models for the estimation of emissions from transport, and an overview of the ARTEMIS project.

A2 International legislation, reporting obligations and activities

A2.1 Legislative context

Individual countries are subject to various international obligations concerning emissions of air pollutants. The main relevant reporting obligations relate to two protocols: the Convention on Long-Range Transboundary Air Pollution, and the United Nations Framework Convention on Climate Change. In addition, the MARPOL convention applies specifically to marine shipping. These are discussed in more detail below.

The Convention on Long-Range Transboundary Air Pollution

The 1979 Geneva Convention on Long-Range Transboundary Air Pollution (CLRTAP) created a framework for controlling and reducing the damage to human health and the environment caused by transboundary air pollution, and was the first international legally-binding instrument to deal with problems of air pollution on a broad regional basis. The Convention was signed by 34 Governments (Parties) and the European Community. CLRTAP entered into force in 1983. The Convention now has 49 Parties, and has been extended by eight protocols that identify specific measures to be taken by Parties:

(i) The 1984 Geneva Protocol on Long-term Financing of the Cooperative Programme for Monitoring and Evaluation of the Long-range Transmission of Air Pollutants in Europe (EMEP), which entered into force on 28 January 1988.

(ii) The 1985 Helsinki Protocol on the Reduction of Sulphur Emissions or their Transboundary Fluxes by at least 30 per cent, which entered into force on 2 September 1987.

(iii) The 1988 Sofia Protocol concerning the Control of Nitrogen Oxides or their Transboundary Fluxes, which entered into force on 14 February 1991.

(iv) The 1991 Geneva Protocol concerning the Control of Emissions of Volatile Organic Compounds (VOCs) or their

Transboundary Fluxes, which entered into force on 29 September 1997.

(v) The 1994 Oslo Protocol on Further Reduction of Sulphur Emissions, which entered into force on 5 August 1998.

(vi) The 1998 Aarhus Protocol on Heavy Metals, which entered into force on 29 December 2003.

(vii) The 1998 Aarhus Protocol on Persistent Organic Pollutants (POPs), which entered into force on 23 October 2003.

(viii) The 1999 Gothenburg Protocol to Abate Acidification, Eutrophication and Ground-level Ozone, which entered into force on 17 May 2005.

In addition to establishing the general principles of international co-operation for air pollution abatement, the Convention provides an institutional framework linking scientific research and policy. Its scientific Working Groups - the Working Group on Effects and the Steering Body of EMEP - and their task forces and international centres, address the issues that enable the Convention to develop the science-based policies and control measures in its Protocols.

The United Nations Framework Convention on Climate Change

The United Nations Framework Convention on Climate Change (UNFCCC) sets an overall framework for inter-governmental efforts to tackle the challenges posed by climate change. The Convention entered into force on 21 March 1994, having been adopted at the 1992 Rio Earth Summit. Most OECD[1] members, plus the states of Central and Eastern Europe - known collectively as Annex I countries - are committed to adopting policies and measures aimed at reducing their greenhouse gas emissions.

The Kyoto Protocol to the Framework Convention was adopted by consensus at the third session of the Conference of the Parties (‘COP-3’) in December 1997, and contains new emission targets for developed countries. These countries committed themselves to reduce their emissions (calculated as an average over the five-year period 2008-12) of six key greenhouse gases by at least 5% compared with 1990 levels. The Protocol came into force in February 2005 following ratification by Russia. As of February 2006, a total of 162 countries had ratified the agreement.

International Convention for the Prevention of Pollution from Ships

The International Convention for the Prevention of Pollution from Ships (MARPOL[2]) is the main international convention covering prevention of pollution of the marine environment by ships from both routine operations and accidents. It is a combination of two treaties adopted in 1973 and 1978 respectively, and has been updated via a series of amendments. The Convention currently includes six technical Annexes. Annex VI (Air Pollution) came into force in May 2005. It sets limits on emissions of sulphur oxides (SO_x) and nitrogen oxides (NO_x) from ship exhausts, and prohibits deliberate emissions of ozone-depleting substances.

A2.2 Reporting obligations

Pollutants

Parties to CLRTAP are requested to report annual emissions of the following air pollutants: sulphur, NO_x, ammonia (NH_3), non-methane volatile organic compounds (NMVOCs), carbon monoxide, particulate matter, the heavy metals cadmium, lead, mercury, arsenic, chromium, copper, nickel, selenium, and zinc, the persistent organic pollutants aldrin, chlordane, chlordecone, DDT, dieldrin, endrin, heptachlor, hexachlorobenzene, mirex, toxaphene, hexachloro-cyclohexane, hexabromobiphenyl, polychlorinated biphenyls (PCBs), dioxins/furans, polycyclic aromatic hydrocarbons (PAHs), short-chained chlorinated paraffins and pentachlorophenol.

Parties to UNFCCC are requested to report annual emissions of carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O), NO_x, NMVOCs, CO, hydrofluorocarbons (HFCs), perfluorocarbons (PFCs) and sulphur hexafluoride (SF_6). Cuts in the three most important gases - CO_2, CH_4 and N_2O - are measured against a base year of 1990. Cuts in three long-lived industrial gases - HFCs, PFCs and (SF_6) - can be measured against either a 1990 or 1995 baseline.

Years

According to the Protocols, each Party must, for each Protocol to which it is a Party, report on emissions for the base year of the Protocol and every year starting with the year of entry into force of the Protocol for that Party. Emission inventory reporting should cover all years from 1980 onwards, if data are available. Parties within the geographic scope of EMEP should report projected activity data and projected national total emissions for SO_2, NO_x, NH_3 and NMVOCs for the years 2010, 2015 and 2020.

[1] OECD = Organisation for Economic Co-operation and Development
[2] MARPOL = marine pollution

Interaction with the INSPIRE Directive

The Infrastructure for Spatial Information in the Community (INSPIRE) Directive aims at creating a European Spatial Data Infrastructure by improving the interoperability of spatial information across the European Union at a local, regional, national and international level. In doing so it aims to facilitate improvements in the sharing of spatial information between public authorities and provide improved public access to spatial information. The Directive came into force 15 May 2007, as directive 2007/2/EC. The environment is the first theme to be covered under INSPIRE, but it will be eventually extended to other themes such as agriculture and transport.

Previously there was a lack of a formal standard or any central policy on the collection, storing and access to geographical data, and indeed the link between transport emissions and transport activity data have been weakened by this omission. Under the ARTEMIS programme, consideration was therefore given to the availability of transport activity data, and recommendations made on consistent ways of reporting emission data, specifically from road transport.

A2.3 Source sector nomenclature

The nomenclature used in the compilation of emission inventories is described extensively in the EMEP/CORINAIR Emission Inventory Guidebook[3] and supporting documents. A detailed nomenclature was developed for the CORINAIR 1985 Project: SNAP-P (Selected Nomenclature for sources of Air Pollution - Prototype). In 1995, the European Topic Centre on Air Emissions (ETC/AE) developed the CORINAIR nomenclature further, resulting in SNAP94. In 1998 ETC/AE developed the nomenclature still further, resulting in SNAP97. SNAP97 covers additional activities which are sources of heavy metals and POPs, and is fully consistent with the Intergovernmental Panel on Climate Change (IPCC) nomenclature, developed in 1996 for reporting under the UNFCCC. In 1999 UNFCCC also developed the Common Reporting Format (CRF), which is in line with the 1996 IPCC Guidelines. The CRF has been used by countries for the reporting of greenhouse gas inventories since 2000. EUROSTAT has also initiated a project to enable process-oriented source nomenclatures such as SNAP to be more consistent with socio-economic nomenclatures, and to include waste generation processes and emissions to water. This resulted in the NOSE (NOmenclature for Sources of Emissions) manual of May 1998.

In 2001 the UNECE TFEIP developed the NFR (Nomenclature For Reporting) source sector classification system. In the development of NFR a correlation was established between the SNAP, NFR and CRF/IPCC reporting source categories. The compilers of national emission inventories used this format for the first time in the 2002 reporting round.

ARTEMIS is concerned with emissions from transport. The SNAP 97 nomenclature distinguishes between road transport (SNAP 07) and other mobile sources (SNAP 08). However, parties to CLRTAP are encouraged to report more detail. **Tables A-1** and **A-2** show the Correspondence between CORINAIR/SNAP and IPCC classification, and give the level of coverage in ARTEMIS.

A2.4 Air quality legislation

Air Quality Framework Directive and Daughter Directives

A series of Directives has been introduced to control levels of certain pollutants and to monitor their concentrations in the atmosphere. In 1996, the Environment Council adopted Framework Directive 96/62/EC on Ambient Air Quality Assessment and Management. This Directive covers the revision of existing legislation and the introduction of new air quality standards for previously unregulated air pollutants, setting the timetable for the development of specific Daughter Directives for a range of pollutants.

National Emissions ceilings

Directive 2001/81/EC on National Emission Ceilings (NECs) sets upper limits for each Member State on the total emissions in 2010 of the four pollutants responsible for acidification, eutrophication and ground-level ozone pollution (SO_2, NO_x, VOCs and NH_3). The Directive leaves it largely to the Member States to decide which measures to take in order to comply. The emission ceilings are designed to meet interim objectives for acidification that have been agreed by the Council and the Parliament, plus new objectives for ozone, in the lowest-cost way for the Communities as a whole. The pollutants concerned are transported in large quantities across national boundaries, and individual Member States would not generally be able to meet the objectives within their territory by national action alone.

Parallel to the development of the EU NEC Directive, the EU Member States, together with Central and Eastern European countries, the United States and Canada have negotiated a new 'multi-pollutant' protocol under the CLRTAP (the so-called 'Gothenburg Protocol', agreed in November 1999). The emission ceilings in the Gothenburg Protocol are less ambitious than those decided by the Council and Parliament.

[3] http://reports.eea.eu.int/EMEPCORINAIR4/en

Based on the provisions of the Directive, Member States are obliged to report their national emission inventories for each year, and projections for 2010, to the European Commission and the European Environment Agency. They must also draw up national programmes in order to demonstrate how they are going to meet the national emission ceilings by 2010.

The Commission has commenced the preparatory work for a legislative proposal to revise the NEC Directive. This revision will build upon the work performed under the Clean Air For Europe Programme, the Thematic Strategy on Air Pollution, the review of the Directive and the scientific and technical work that is currently ongoing. The new proposal will set emission ceilings to be respected by 2020 for the four already regulated substances and probably for the primary emissions of $PM_{2.5}$ as well. Although some other aspects of the NECD will be revised too, the proposal will not affect the national emission ceilings for 2010. It is currently foreseen that the new proposal will be adopted during 2007. The objectives of the revised NECD will be similar to the objectives of the Thematic Strategy on Air Pollution.

A2.5 International bodies and activities

European Commission

The European Commission is a politically independent collegial institution which embodies and defends the general interests of the EU. Its virtually exclusive right of initiative in the field of legislation makes it the driving force of European integration. It prepares and then implements the legislative instruments adopted by the Council and the European Parliament, in connection with Community policies. The Commission also has powers of implementation, management and control. It is responsible for planning and implementing common policies, executing the budget and managing Community programmes, and also ensures that European law is applied.

European Environment Agency

The European Environment Agency (EEA) was established by EEC Regulation 1210/1990, and became operational in 1994. Its headquarters are in Copenhagen, Denmark. It is the EU body devoted to establishing a network for the monitoring of the environment. The EEA is dedicated to providing sound, independent information on the environment, and is a major source of information for those involved in developing, adopting, implementing and evaluating environmental policy. The EEA is governed by a board composed of representatives of the governments of Member States, a European Commission representative, and two scientists appointed by the European Parliament, assisted by a scientific committee.

European Topic Centre on Air and Climate Change

The European Topic Centre on Air and Climate Change (ETC/ACC) assists the EEA in its support of EU policy in the field of air pollution and climate change. It is a consortium of 14 European institutions, established in 2001 by the EEA. The ETC/ACC reports on the progress of EU environmental policy on air quality, air pollutant emissions and climate change issues. It participates in relevant reports issued the EEA, collects data concerning the current state of the environment, and harmonises European air quality monitoring networks and reporting obligations.

Clean Air for Europe

Clean Air For Europe (CAFE), which was launched in March 2001, is a programme of technical analysis and policy development which underpinned the development of the Thematic Strategy on Air Pollution under the Sixth Environmental Action Programme. The aim of CAFE was to develop long-term, strategic and integrated policy advice to combat the adverse effects of air pollution on human health and the environment. The implementation of the Thematic Strategy on Air Pollution began in September 2005. The technical work was undertaken by the International Institute of Applied Systems Analysis (IIASA) using the RAINS integrated assessment model.

European Climate Change Programme

The European Climate Change Programme (ECCP) was established in June 2000 to help identify the most environmentally effective and cost-effective measures to enable the EU to meet its target under the Kyoto Protocol (*i.e.* an 8% reduction in greenhouse gas emissions from 1990 levels by 2008-2012). In October 2005 the European Commission launched a new phase of the European Climate Change Programme (ECCPII). Key aspects of ECCPII include geological carbon capture and storage, adaptation, aviation, passenger road transport, energy efficiency, renewable energy and technology policy.

Table A-1: Correspondence between CORINAIR/SNAP, UNFCCC and EMEP classification, and coverage in ARTEMIS – road transport.

CORINAIR/SNAP97 classification				UNFCCC and EMEP classifications			Included in ARTEMIS
Level			Name of activity	UNFCCC CRF	EMEP NFR (2002)	Name of activity	
L1	L2	L3					
07			**Road transport**				
07	**01**		**Passenger cars**	1A3b	1A3b i	Road Transportation, Passenger Cars	✓
07	01	01	Highway driving	1A3b	1A3b i	Road Transportation, Passenger Cars	✓
07	01	02	Rural driving	1A3b	1A3b i	Road Transportation, Passenger Cars	✓
07	01	03	Urban driving	1A3b	1A3b i	Road Transportation, Passenger Cars	✓
07	**02**		**Light-duty vehicles <3.5 t**	1A3b	1A3b ii	Road Transportation, Light-duty vehicles	✓
07	02	01	Highway driving	1A3b	1A3b ii	Road Transportation, Light-duty vehicles	✓
07	02	02	Rural driving	1A3b	1A3b ii	Road Transportation, Light-duty vehicles	✓
07	02	03	Urban driving	1A3b	1A3b ii	Road Transportation, Light-duty vehicles	✓
07	**03**		**Heavy-duty vehicles >3.5t and buses**	1A3b	1A3b iii	Road Transportation, Heavy-duty vehicles	✓
07	03	01	Highway driving	1A3b	1A3b iii	Road Transportation, Heavy-duty vehicles	✓
07	03	02	Rural driving	1A3b	1A3b iii	Road Transportation, Heavy-duty vehicles	✓
07	03	03	Urban driving	1A3b	1A3b iii	Road Transportation, Heavy-duty vehicles	✓
07	**04**		**Mopeds and motorcycles <50cm3**	1A3b	1A3b iv	Road Transportation, Mopeds and motorcycles	✓
07	**05**		**Motorcycles >50cm3**	1A3b	1A3b iv	Road Transportation, Mopeds and motorcycles	✓
07	05	01	Highway driving	1A3b	1A3b iv	Road Transportation, Mopeds and motorcycles	✓
07	05	02	Rural driving	1A3b	1A3b iv	Road Transportation, Mopeds and motorcycles	✓
07	05	03	Urban driving	1A3b	1A3b iv	Road Transportation, Mopeds and motorcycles	✓
07	**06**		**Gasoline evaporation from vehicles**	-	1A3b v	Gasoline Evaporation from vehicles	✓
07	**07**		**Automobile tyre and brake wear**	-	1A3b vi	Automobile tyre and brake wear	✗
07	**08**		**Automobile road abrasion**	-	1A3b vii	Automobile road abrasion	✗

Table A-2: Correspondence between CORINAIR/SNAP, UNFCCC and EMEP classification, and coverage in ARTEMIS – other sectors.

CORINAIR/SNAP97 classification				UNFCCC and EMEP classifications			Included in ARTEMIS
Level			Name of activity	UNFCCC CRF	EMEP NFR (2002)	Name of activity	
L1	L2	L3					
08			**Other mobile sources and machinery**				
08	**0**		**Military**	1A5b	1A5b	Other, Mobile (including military)	×
08	**0**		**Railways**	1A3c	1A3c	Transport-Railways	×
08	0	0	Shunting locos	1A3c	1A3c	Transport-Railways	✓
08	0	0	Rail-cars	1A3c	1A3c	Transport-Railways	✓
08	0	0	Locomotives	1A3c	1A3c	Transport-Railways	✓
08	**0**		**Inland waterways**	1A3d	1A3d ii	Transport-Navigation, National navigation	✓
08	0	0	Sailing boats with auxiliary engines	1A3d	1A3d ii	Transport-Navigation, National navigation	×
08	0	0	Motorboats / workboats	1A3d	1A3d ii	Transport-Navigation, National navigation	×
08	0	0	Personal watercraft	1A3d	1A3d ii	Transport-Navigation, National navigation	×
08	0	0	Inland goods carrying vessels	1A3d	1A3d ii	Transport-Navigation, National navigation	✓
08	**0**		**Marine activities**				✓
08	0	0	National sea traffic within EMEP area	1A3d	1A3d ii	Transport-Navigation, National navigation	✓
08	0	0	National fishing	1A4c	1A4c iii	Small combustion-Agriculture/Forestry/Fishing	×
08	0	0	International sea traffic	1A3d	1A3d i	Transport-Navigation, International marine (bunkers)	✓
08	**0**		**Air traffic**				
08	0	0	Domestic airport traffic (LTO cycles <1000m)	1A3a ii	1A3a ii (i)	Transport-Civil aviation, Domestic, LTO	✓
08	0	0	International airport traffic (LTO cycles <1000m)	1A3a i	1A3a i (i)	Transport-Civil aviation, International, LTO	✓
08	0	0	National cruise traffic (>1000m)	1A3a ii	1A3a ii (ii)	Transport-Civil aviation, Domestic, Cruise	✓
08	0	0	International cruise traffic (>1000m)	1A3a i	1A3a i (ii)	Transport-Civil aviation, International, Cruise	✓
08	**0**		**Agriculture**	1A4c	1A4c ii	Small combustion-Agric./Forestry/Fishing – Off-road vehicles & other machinery	×
08	**0**		**Forestry**	1A4c	1A4c ii	Small combustion-Agric./Forestry/Fishing – Off-road vehicles & other machinery	×
08	**0**		**Industry**	1A2 a-f	1A2 a-f	Industry	×
08	**0**		**Household and gardening**	1A4b	1A4b ii	Small combustion-Residential, Household and gardening (mobile)	×
08	**1**		**Other off-road**	1A3e	1A3e ii	Transport-Other, Other mobile sources and machinery	×

Co-operative Programme for Monitoring and Evaluation of the Long-Range Transmission of Air Pollutants in Europe

The main objective of the Co-operative Programme for Monitoring and Evaluation of the Long-Range Transmission of Air Pollutants in Europe (EMEP) is to regularly provide governments and subsidiary bodies with qualified scientific information to support the development and further evaluation of the international protocols on emission reductions negotiated within the CLRTAP. EMEP relies on three main elements: (i) collection of emission data, (ii) measurements of air and precipitation quality and (iii) modelling of atmospheric transport and deposition of air pollution. EMEP regularly reports on emissions, atmospheric concentrations and/or depositions of pollutants, the quantity and significance of transboundary fluxes, and related exceedences of critical loads and threshold levels. The combination of these components also provides a basis for the evaluation and qualification of the EMEP estimates.

Task Force on Emission Inventories and Projections (TFEIP)

The Task Force on Emission Inventories (TFEI) was initiated in 1991 following agreement by the Executive Body of the Convention on Long-Range Transboundary Air Pollution. In 1995 the TFEI combined with the Task Force on Emission Projections to become the Task Force on Emissions Inventories and Projections (TFEIP). The TFEIP is supported by the other signatories to the Convention, including the European Community, through the European Commission and the European Environment Agency (EEA). The TFEIP is designed to assist in the following:

- The evaluation of the emission inventory requirements of EMEP.
- Ensuring an adequate flow of reliable information to support the work under CLRTAP.
- Accounting for the emission data needs of other relevant bodies under the Executive Body.

The objectives of the TFEIP are therefore:

- To provide a technical forum to exchange information and harmonise emission inventories, including emission factors, methodologies and guidelines.
- To conduct in-depth evaluations of the emission factors and methodologies in current use.
- To co-operate with other international organisations working on emission inventories, with the aim of harmonising methodologies and avoiding duplication of work.

In 1993 the TFEI agreed a specification for the EMEP/CORINAIR Emission Inventory Guidebook. The first edition of the Guidebook was subsequently completed in 1996 and published and distributed by the EEA. The third edition of the Guidebook was published in 2004.

COST

Founded in 1971, COST[4] is an inter-governmental framework for European Co-operation in Scientific and Technical Research which allows the co-ordination of nationally-funded research on a European level. COST Actions cover basic and pre-competitive research, as well as activities of public utility. The goal of COST is to ensure that Europe holds a strong position in the field of scientific and technical research for peaceful purposes, by increasing European co-operation and interaction in this field. COST has developed into one of the largest frameworks for research co-operation in Europe. At present it has almost 200 Actions, and involves nearly 30,000 scientists from 34 European member countries and 11 non-member countries. Relevant examples of Actions include COST 319, which dealt with the estimation of pollutant emissions from transport, and COST 346[5] which focussed specifically on emissions from heavy-duty vehicles.

A3 Existing emission factors and models for transport sources

Prior to ARTEMIS, several different transport-related emission models were used in the compilation of emission inventories in Europe. Some of these models are briefly summarised below.

MEET

The European Commission's 4th Framework project MEET (Methodologies for Estimating air pollutant Emissions from Transport) provided a basic Europe-wide procedure for evaluating the impact of transport on air pollutant emissions and energy consumption. It brought together the most comprehensive and up-to-date information on emission rates and activity statistics, which made it possible to estimate the emissions resulting from almost any transport operation. The modes included were road transport, railways, water transport (inland and marine, but excluding leisure activities and fishing), and air traffic. A variety of methods were used to calculate energy consumption and emissions, depending on the pollutant, the transport mode and the vehicle type (European Commission, 1999).

[4] http://www.cost.esf.org/index.php
[5] http://www.cordis.lu/cost-transport/src/cost-346.htm

TREMOVE

TREMOVE[6] is a policy assessment model which has been designed to aid the study of the effects of different transport and environment policies on emissions from the transport sector. The model can be used to assess the effects of policies on transport demand, modal shift, vehicle stock renewal and scrappage decisions, as well as the emissions of air pollutants. The model covers passenger and freight transport in 21 European countries, and covers the period 1995-2030. The baseline scenario as well as results of policy simulations will be crucial inputs for CAFE and the ECCP, as well as for other programmes. The most recent version is TREMOVE 2.40, which was released in September 2005. The TREMOVE data are available in the form of a Microsoft Access database. The database contains four queries (stock, demand, welfare and emissions), and presents data for all 21 countries.

TRENDS (TRansport and ENvironment Database System)

The TRENDS project was funded by the European Commission Directorate General for Transport and Energy. The project involved several institutes and organisations, some of which also participated in ARTEMIS, and was completed in 2002. The purpose of TRENDS was to develop a system for calculating a range of transparent, consistent and comparable indicators relating to the environmental 'pressures' due to transport. These included atmospheric emissions from the four main transport modes (road, rail, shipping and air), waste generation and noise emissions from road transport. The indicators were calculated directly from the activity levels, and reflect the potential change in the state of the environment, or the risk of specific environmental impacts which any changes in policy might have. The TRENDS system also provides an option for simple scenario analysis for EU Member States.

COPERT

COPERT[7] is a program which can be used to calculate emissions of air pollutants from road transport. The development of COPERT has been financed by the EEA as part of the activities of the European Topic Centre on Air and Climate Change. The initial version of the program, COPERT 85 (1989), was followed by COPERT 90 (1993) and COPERT II (1997). COPERT III (Ntziachristos and Samaras, 2000) is the third update of the methodology. The current version draws its main principles from several European activities, including COST 319, MEET, and the European Commission Inspection and Maintenance Programme. COPERT III estimates emissions of all regulated air pollutants (CO, NO_x, VOC, PM) from different vehicle categories, as well as CO_2 emissions and fuel consumption. Furthermore, emissions are calculated for an extended list of non-regulated pollutants, including CH_4, N_2O, NH_3, SO_2, heavy metals, PAHs and POPs, and speciated hydrocarbons. Emissions are generally distinguished according to three sources: (i) thermally-stabilised engine operation (hot emissions), (ii) engine starts (cold-start emissions) and (iii) NMVOC emissions due to fuel evaporation.

Handbook of Emission Factors

The Handbook of Emission Factors (HBEFA) is a road transport emission model which is used for both national inventories and local applications in Germany, Austria and Switzerland. The model is based on reference emission factors for different categories of vehicle. Each emission factor is associated with a particular 'traffic situation', characterised by the features of the section of road concerned (*e.g.* 'motorway with 120 km/h limit', 'main road outside built-up area'). The variability of traffic speed for a given traffic situation is defined via a textual description (*e.g.* 'free-flow', 'stop-and-go') (INFRAS, 2004). The emission factors produced by the Handbook for the various vehicle categories must then be weighted according to traffic flow and composition.

A4 The ARTEMIS project

A4.1 Objectives

The need for reliable knowledge concerning the sources and causes of air pollution was stressed at the beginning of this Part of the Report. In addition, in order to determine the most effective pollution-reduction strategies the most important technological and behavioural parameters must be identified, and the effects of these parameters quantified.

A basic requirement of emission models is that they should be capable of producing accurate, reliable and consistent results. However, comparisons between the results from several models have highlighted substantial differences, and for a number of reasons, and that there are significant gaps in the data. Using road transport as an example, in COST 319 and MEET it was shown that whilst a large number of emission measurements had been performed on road vehicles, less than 1% of the available data related to heavy-duty vehicles. Consequently, although road freight transport is recognised as a major source of pollution, the understanding of the emission behaviour of this group of vehicles was comparatively poor. The lack of relevant data on traffic characteristics (activity and operating conditions) was also a significant source of uncertainty in

[6] http://www.tremove.org/
[7] http://vergina.eng.auth.gr/mech0/lat/copert/copert.htm

emission estimates. Emission estimates for non-road transport are particularly uncertain, and the research effort for rail, shipping and air transport has generally been less extensive than that for road transport.

The ARTEMIS project represented a combination of three fifth framework (FP5), first call submissions:

- REF - Reliable Emission Factors, co-ordinated by INRETS,
- ABLE - Assessment of Bus and Lorry Emissions, co-ordinated by TUG,
- ARTEMIS - Assessment of Road Transport Emission Models and Inventory Systems, co-ordinated by INFRAS.

These three projects, combined with the PARTICULATES project co-ordinated by LAT, were submitted in response to Sub-Task 2.2.2/2: Monitoring emissions from transport, as an 'ex-ante' cluster. During the negotiation period the REF, ABLE and ARTEMIS projects were combined under a single project, including non-road emissions, traffic statistics and software development. These activities were combined under the ARTEMIS umbrella, subsequently co-ordinated by TRL. The PARTICULATES project was commissioned as a separate, but associated project.

The ARTEMIS project thus commenced in 2000, and had two principal objectives. The first of these was to gain, through a programme of basic research, a better understanding of the causes of the differences in model predictions, and thus to address the uncertainties in emission modelling. The project included a large emission measurement programme, designed to provide a significant extension to the available databases. For road transport, measurements conducted in many laboratories around Europe were used to examine the reasons for variability in the data, and to form the basis of a 'best practice' guide for future measurements. The resources devoted to the work on non-road transport modes were also increased to ensure that the associated models would be greatly improved. The second principal objective was to develop a harmonised methodology for estimating emissions from all transport modes at the national and international levels.

At the outset, it was considered that some of the reasons for the discrepancies between different emission models might be institutional in nature, such as the lack of communication and the use of different databases describing the same phenomena. In order to achieve a higher level of consistency, ARTEMIS established a research group to improve the co-ordination of the research activities.

The specific objectives of ARTEMIS can be summarised as follows:

(i) To extend existing emission models, their underlying data, and their methodologies, so that they will be able to incorporate not only the known influential parameters, but also future emission factors which might require additional external information (*e.g.* use of air conditioning devices, new engine or pollution control concepts).

(ii) To make emission models and inventories more consistent between applications at different levels of spatial resolution. This includes both the types of emission factor to be applied and the description of traffic characteristics.

(iii) To improve co-ordination, increase efficiency, and generally make better use of available resources, information and tools via the creation of a specific research group for emission estimations. It was expected that this group would also enable better access to national data as a prerequisite for more consistent inventories.

(iv) To better validate emission models in order to improve inventories and their underlying emission factors, and to improve credibility.

(v) To make information available to a broad range of users in the form of a user-friendly tool.

A4.2 Consortium

ARTEMIS was a large and very diverse project which benefited from the participation of a large consortium, including many of the relevant key organisations in Europe. The 37 partners of the consortium, which came from 14 countries, are listed in **Table A-3**. The project was co-ordinated by TRL Limited, with assistance from a project co-ordination committee. Contact details for the ARTEMIS participants are given at the end of this Report.

A4.3 Work programme

The main tasks of the ARTEMIS project are listed below. The specific measurement and modelling methodologies for each transport mode are presented in the relevant Parts of the Report.

Table A-3: Partners in the ARTEMIS consortium.

Participant number	Name	Abbreviation	Country
1	TRL Limited	TRL	United Kingdom
2	Technical University of Denmark	DTU	Denmark
3	INFRAS AG Forschung, Wirtschafts- und Umweltberatung	INFRAS	Switzerland
4	Institut National de Recherche sur les Transports et leur Securité	INRETS	France
5	Institute for Internal Combustion Engines and Thermodynamics, Technical University of Graz	TUG	Austria
6	Aristotle University Thessaloniki, Laboratory of Applied Thermodynamics	AUTH/LAT	Greece
7	Netherlands Organisation for Applied Research	TNO	Netherlands
8	PsiA Consult Umweltforschung und Engineering GmbH	PsiA	Austria
9	Flygtekniska Forsoksanstalten Aeronautical Research Institute of Sweden	FFA/FOI	Sweden
10	AVL List GmbH	AVL	Austria
11	Bergische Universitat - Gesamthochschule Wuppertal	BUGHW	Germany
12	PPW Czyste Powietrze	PPW	Poland
13	Abgasprufstelle Fachhochschule Biel	AFHB	Switzerland
14	Institut fur Meteorologie und Klimaforschung, Atmosphaerische Umweltforschung, Forschungszentrum Karlsruhe GmbH	FZK/IMK-IFU	Germany
15	Kozlekedestudomanyi Intezet RT - Institute for Transport Sciences	KTI	Hungary
16	National Research Council of Italy	CNR	Italy
17	European Commission Joint Research Centre	JRC	Italy
18	Paul Scherrer Institute	PSI	Switzerland
19	Régie Autonome des Transports Parisiens	RATP	France
20	Renault Research Innovation	REGIENOV	France
21	Université des sciences et Technologies de Lille	USTL	France
22	Swedish Environmental Research Institute Ltd.	IVL	Sweden
23	Swiss Federal Institute of Technology, Zurich	ETHZ	Switzerland
24	Swiss Federal Laboratories for Materials Testing and Research	EMPA	Switzerland
25	Technical Research Centre of Finland	VTT	Finland
26	TECHNION, Israel Institute of Technology	TECHNION	Israel
27	TRAFICO Verkehrsplanung	TRAFICO	Austria
28	Université du Littoral Côte d'Opale	ULCO	France
29	Lund University	LU	Sweden
30	Université de Savoie-Esigec	US	France
31	Vlaamse Instelling voor Technologisch Onderzoek	VITO	Belgium
32	RWTUEV Fahrzeug GmbH	RWTUEV	Germany
33	TUEV Nord Strassenverkehr GmbH	TUV Nord	Germany
34	MariTerm AB	MariTerm	Sweden
35	FH Joanneum Gesellschaft mbH	FHJ	Austria
36	Motortestcentre	AVL-MTC	Sweden
37	Swedish National Road and Transport Research Institute	VTI	Sweden

European Transport Emissions Research Group

In order to arrive at a harmonised methodology, additional effort at the institutional level was considered necessary. Therefore, ARTEMIS established a specific 'European Transport Emissions Research Group' (ETERG) which involved members of the EU (European Commission, EEA) as well as representatives of the Member States and other stakeholders. ETERG was designed to allow a better exchange of information and experiences between countries, and to increase the acceptability of the ARTEMIS results. The remit of ETERG was defined in terms of three different tasks:

- *A scientific task*: to assess the state of the art in emission modelling and to identify the relevant gaps, taking into account national programmes and research projects proposed within the 5th Framework, and to provide a peer review of this work.
- *A co-ordination task*: to co-ordinate similar research projects on the national levels, and other tasks of the 5th Framework, in order to produce coherent results.
- *An application task*: to guarantee the links between the research teams and the relevant national bodies.

Road transport

Road traffic characteristics

This aspect of the work focused on the collection, processing, adaptation or application of existing data, and the improvement or extension of the modelling approaches relating to fleets, usage and driving conditions of road vehicles in EU and CEEC countries. The data collection covered all relevant aspects of vehicle operation including, for example, trip profiles and the use of auxiliaries, in addition to the more general information on vehicle types and distances travelled. The sensitivity of emission estimates to traffic-related parameters was also considered.

Establishment of reliable emission factors for passenger cars and light commercial vehicles

An investigation was conducted into the reasons for the differences between emission measurements at different laboratories, and a best practice procedure for measurement was designed. Measurements of regulated and unregulated pollutants from vehicles equipped with the latest emission-control technologies were undertaken, and assessments were made of the effects of road gradient and ambient temperature on emissions. An improved emission calculation model was then developed.

Establishment of reliable emission factors for heavy-duty road vehicles (HDVs)

This part of the ARTEMIS work involved the development of a detailed model for estimating energy consumption and emissions over any driving cycle. The calculation of energy consumption and exhaust gas emissions used engine maps from steady-state measurements as the basic input data. Correction functions for transient engine torque and engine speed, which occur in real-world traffic, were then developed. This approach facilitated the modelling of the effects of different vehicle specifications, different vehicle loads, and different road and traffic conditions.

Emission factors for two-wheel vehicles

Prior to ARTEMIS there was no widely-accepted test procedure for determining emission factors for two-wheel vehicles. The basic concern was the that the commonly-used ECE15 test cycle was very unrealistic compared with real-world driving, and was based on the operation of passenger cars rather than two-wheel vehicles. In order to address this problem, real-world driving patterns were recorded and used for chassis dynamometer tests, and existing real-world test cycles for four-wheel vehicles were modified for use with two-wheel vehicles. Based on the data from the measurements, an emission factor model for two-wheel vehicles was developed. The effects of cold start, inspection and maintenance and fuel properties were also addressed.

Improved cold-start emissions modelling

An improved method was developed for the modelling of cold-start emissions from passenger cars, taking into account factors such as ambient temperature, speed, and parking duration.

Measurement of evaporative emissions from light-duty vehicles and motorcycles

Evaporative losses represent a significant source of VOC emissions from the light-duty vehicle sector. Prior to ARTEMIS, only very limited information was available on evaporative emissions and the effectiveness of control systems. The existing methodologies for the calculation of evaporative emissions were reviewed, and new measurements were performed to fill some of the gaps.

Validation of road transport model

The emission behaviour of the road vehicle fleet is influenced by many parameters, and large numbers of laboratory tests are required to obtain statistically reliable data. It is therefore desirable to use alternative methods to validate the emission data from laboratory tests, or adjust them to real-world conditions. Road tunnels can be used to measure emissions from in-use vehicles under real-world conditions. In this part of the ARTEMIS work measurements were conducted in three tunnels for the purpose of model validation.

Rail transport

The aim of the ARTEMIS work on rail transport was to develop a model which was open and accessible for future modification, and could be used in a database format. The work began with a re-evaluation of representative categories of train. Categories were identified to represent sectors which could be readily identified on a technical basis, and for which model users could obtain information. A number of train types and traffic-related conditions were selected for detailed investigation, and the energy consumption of these types of train was evaluated. Exhaust emissions were estimated using existing emission factors; an attempt was made to obtain emissions data for an additional number of engines, but no new measurements were conducted. The results were used to define average emission characteristics for the chosen train classifications. Since strategic comparisons of transport modes involve systems to be constructed in the future, it was also necessary to predict future developments in rail transport.

Inland shipping

Although detailed procedures were available prior to ARTEMIS for the calculation of the fuel consumption of inland waterway vessels, for strategic emission evaluation and inventories these models, whilst accurate, were too complicated and demanded a level of expertise that exceeded that of model users. ARTEMIS aimed to provide a better understanding of the factors influencing vessel operation on inland waterways. The existing methodologies were further developed, based on experimental data and carefully selected calculations for representative ships and conditions. In evaluating the role of inland shipping, there was a need for tools which could be used to provide an overview of air pollutant emissions attributable to each operational mode, and to produce indicators for specific categories of vehicle, goods and geographical area of operation, so that both the present situation and the effects of possible modal shift scenarios could be evaluated. This would help support decisions regarding administrative or infrastructure changes aimed at promoting certain modes of transport.

Maritime shipping

For seagoing ships, the aim of the ARTEMIS work was to provide a better verification of model accuracy, and to improve the knowledge of operational conditions and fuel consumption in harbour environments. Also, a better description of ferry operation was needed, in terms of ship size, fuel consumption and loading.

Air transport

The basic objective in terms of air transport was to close the gaps between the air traffic emissions research community and the average user of methodologies for air traffic emission inventories. Knowledge on emission characteristics has been improved in recent years through EU-sponsored research projects such as POLINAT and AEROCERT, but little practical use is made of this information in air traffic emission estimates which serve the needs of international reporting mechanisms. In ARTEMIS, some of the most important gaps were closed by updating the existing emission database (primarily MEET data) to take account of the following:

(i) The in-flight situation (focusing on the influence of cruise ambient temperatures on emissions).

(ii) Ground operations, such as emissions arising during engine start-up.

(iii) The influence of maintenance and engine age on emissions.

(iv) The aircraft/engine combinations not covered in the existing database (*e.g.* turboprops, new airframes, or former Soviet aircraft).

Inventory model development

The objectives of this part of the work were:

(i) To assemble a detailed methodology for the calculation of emissions from different transport modes.

(ii) To transfer the method into a menu-driven, user-friendly computer program (using the Windows environment).

(iii) To conduct a statistical assessment of the uncertainties at all stages of the modelling process.

Important*: The length and complexity of this Report means that there will inevitably be a number of typographical errors. Where modelling work is to be conducted, it is strongly recommended that this work is conducted using the actual software tools developed within ARTEMIS, rather than using the information presented here.*

A5 References

European Commission (1999). MEET: Methodology for calculating transport emissions and energy consumption. ISBN 92-828-6785-4.

INFRAS (2004). Handbook of Emission Factors for Road Transport. Version 2.1. INFRAS, Berne, Switzerland.

Ntziachristos L and Samaras Z (2000). COPERT III. Computer program to calculate emissions from road transport. Methodology and emission factors (version 2.1). Technical Report No. 49. European Environment Agency, Copenhagen.

PART B: ROAD TRANSPORT

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B1 OVERVIEW

The history of road transport emission modelling is longer than that of the other transport modes, and in many models the modules dealing with road transport are often the most complex. This complexity was reflected in the ARTEMIS project as a whole, and therefore in this Part of the Final Report. Consequently, a brief introductory explanation of this part of the report is provided here.

In recognition of the contribution of vehicle emissions to air pollution, measures have been taken to reduce the quantities of pollutants emitted. Since the early 1970s, limits have been applied to permissible levels of pollutants in vehicle exhaust. The limits have been reduced many times since they were introduced, and changes have been made to the test method to make it more realistic and effective. All Member States within the EU are subject to the emission limits for road vehicles and engines, and methods of measurement are standardised in European legislation. For the purpose of emission standards and other vehicle regulations, vehicles are classified according to the categories listed in **Table B1-1**. Light commercial vehicles (N1) are further divided into the three weight classes.

Table B1-1: Definition of road vehicle categories.

Category	Description
M	Motor vehicles with at least four wheels designed and constructed for the carriage of passengers.
M_1	Vehicles comprising no more than eight seats in addition to the driver's seat.
M_2	Vehicles comprising more than eight seats in addition to the driver's seat, and having a maximum mass not exceeding 5 tonnes.
M_3	Vehicles comprising more than eight seats in addition to the driver's seat, and having a maximum mass exceeding 5 tonnes.
N	Motor vehicles with at least four wheels designed and constructed for the carriage of goods.
N_1	Vehicles having a maximum mass not exceeding 3.5 tonnes.
	Class I, Class II, Class III: Weight-related distinction, which is dependent upon the actual emission legislation.
N_2	Vehicles having a maximum mass exceeding 3.5 tonnes but not exceeding 12 tonnes.
N_3	Vehicles having a maximum mass exceeding 12 tonnes.
O	Trailers (including semi-trailers).
G*	Off-Road Vehicles.

* Symbol G shall be combined with either symbol M or N. For example, a vehicle of category N_1 which is suited for off-road use shall be designated as N_1G.

European Union emission regulations for new light-duty vehicles (cars and light commercial vehicles) are specified in the Directive 70/220/EEC. This Directive was amended a number of times, with some of the most recent of which amendments including:

- Euro I standards - Directives 91/441/EEC (cars) and 93/59/EEC (cars and light trucks)
- Euro II standards - Directives 94/12/EC and 96/69/EC
- Euro III standards (2000) - Directive 98/69/EC
- Euro IV standards (2005) - Directive 98/69/EC
- Euro V standards (2008) - Proposed regulation.

For heavy-duty vehicles, European emission standards apply to all motor vehicles with a 'technically permissible maximum laden mass' of more than 3,500 kg, equipped with compression ignition, positive ignition natural gas or LPG engines. This covers a wide range of vehicles, and the engine and the body are usually built by separate companies. In order to avoid the complexity and cost of a separate type approval procedure for all varieties of vehicle, the responsibility for compliance with emissions regulation is borne by the engine manufacturer. The regulations for heavy-duty engines were originally introduced by the Directive 88/77/EEC, followed by a number of amendments. Some of the most recent amendments include the following:

- Euro I standards (1992) - Directive 91/542/EEC
- Euro II standards (1996) - Directive 91/542/EEC
- Euro III standards (2000) - Directive 1999/96/EC
- Euro IV/V standards (2005/2008) - Directive 1999/96/EC

In ARTEMIS, a wide range of investigations were conducted in relation to emissions from road vehicles. The measurement programmes and the resulting models were rather complex, and cannot be reproduced in full here. The main aim of Part B of this Report is to provide the reader with a general impression of the type of work conducted during the project. References are made to the many separate report which deal with specific aspects of measurement and modelling, and these reports should be consulted where more detailed information is required. Part B is divided into the following Sections, which reflect the structure of the ARTEMIS work on road transport:

B2 Road traffic characteristics. Previous work has shown that the description of traffic characteristics is a weak link in the modelling of emissions from road transport, and extensive work was conducted in ARTEMIS to address this problem. Furthermore, the work on road traffic characteristics provided vital information on vehicle classification and operational characteristics for the development of overall the road transport model.

B3 Passenger cars. In the MEET project and the COST 319 Action, emission factors for passenger cars were developed using existing data in Europe. However, one of the main conclusions was that there were large differences between the emission levels measured at different laboratories and within individual vehicle categories. In order to produce more accurate emission factors for current and near-future vehicle technologies, a two-fold strategy was therefore adopted in ARTEMIS. Firstly, between-laboratory differences were investigated via a measurement programme, and the sensitivity of pollutant emissions to parameters relating to driving behaviour, vehicles, vehicle sampling and laboratories was investigated. Some of these issues were addressed via reviews of the literature, or by the processing of existing emissions data. For others, new laboratory measurements were required. Secondly, methods were developed to allow the harmonisation of European emission measurement. A further objective was the design of a best practice guide for measuring emissions.

B4 Light commercial vehicles. Existing emission factors for light commercial vehicles were based upon data obtained from passenger cars. Furthermore, only pre-Euro I and Euro I vehicles were included and the emission factors only took into account average speed. In ARTEMIS, new emission factors have been developed which take into account average speed and vehicle load.

B5 Heavy-duty vehicles. The ARTEMIS work on heavy-duty vehicles featured close co-operation with the COST Action 346 and the Handbook of Emission Factors project, and provided a great deal of insight into the emission behaviour of modern vehicles. The main aims of the HDV work were to collect a large amount of emission data from a range of sources, to develop a model capable of accurately simulating emission factors for all types of vehicle and operational condition, to acquire the necessary model input data, and to generate a database of emission factors for the ARTEMIS inventory model.

B6 Two-wheel vehicles. When the ARTEMIS project began, only a few emission models were available for two-wheel vehicles. Models generally used a methodology which was based upon emission tests conducted mainly measured in Switzerland before 1996. More recent emission results were available, but these tended to be based on the type approval cycle and relatively new motorcycles. The representativeness of these test results was therefore in doubt. Because of the diversity of motorcycles and their potential for high speeds and high accelerations, real-world driving was considered to be significantly different from that of cars. Extensive additional measurements on in-use vehicles over real-world test cycles were therefore conducted.

B7 Cold-start emissions. During the period following an engine start, emissions and fuel consumption are elevated as a result of incomplete combustion of the fuel in the engine, the low conversion rate of pollutants in the catalyst, increased viscous friction due to the low lubricant temperature in the engine and transmission, and increased rolling resistance in the tyres. These ‘cold-start’ emissions can constitute a significant proportion of the total of road transport emissions, particularly in urban areas. One of the tasks of ARTEMIS was to improve the modelling of cold-start emissions from passenger cars.

B8 Evaporative emissions. A further objective of ARTEMIS was to develop a model for estimating evaporative emissions from passenger cars and two-wheel vehicles. The model was based mainly upon existing information in the literature, and some basic experiments were conducted to fill the main gaps in the existing data.

B9 Validation. The final aspect of the work involved the validation of emission factors for road transport, based upon air pollution and traffic measurements conducted in three tunnels.

B2 ROAD TRAFFIC CHARACTERISTICS

B2.1 Background

The ARTEMIS work on road traffic characteristics was reported in detail by André *et al*. (2006). This Section of the Report presents a summary of this work. Detailed results are not given, but references to specific technical reports are provided.

Previous work has shown that the description of traffic characteristics is a weak link in the modelling of emissions from road transport. There are two main reasons for this:

(i) Road traffic statistics are often inconsistent. For example, large discrepancies have been observed between different estimates of road network length, traffic volume and the vehicle fleet in some countries (André *et al*., 1999). The available statistics do not normally allow for a reliable spatial distribution of transport activity, and are not always compatible with the requirements of an accurate emission calculation procedure. There is also a general lack of information on the vehicle operating conditions which are relevant to emissions, such as speed, the use of auxiliaries (air conditioning in particular), and vehicle thermal state.

(ii) Emission estimates are highly sensitive to the quality with which parameters such as those given above are described. For example, calculations have shown that the use of speed distributions instead of average values could affect emission estimates by as much as 30%, whilst the definition of the spatial distribution of traffic (and speed) can lead to further uncertainty in the predictions (André and Hammarström, 2000).

Although traffic statistics were available from studies prior to ARTEMIS (*e.g.* MEET, TRENDS), their quality and applicability were questionable. For better forecasts of vehicle fleets and usage, the existing approaches needed to be improved and validated. As part of ARTEMIS and COST346, comprehensive studies of road traffic characteristics were performed in order to address these issues.

The ARTEMIS work on road traffic characteristics covered the following areas:

(i) *A review of existing information on road traffic characteristics*. Careful consideration was given to the data requirements for emission models, and to the needs of model users. The work conducted in COST319 and MEET identified the extent to which available statistics met the objectives of emission modelling. ARTEMIS aimed to combine existing statistics from national and international databases, and to ensure access to these data. It was also necessary to design tools and protocols for the management of data (databases, software, *etc*.). A large number of recommendations resulted from this review.

(ii) *A review of traffic data requirements.* Before the collection of data began, an analysis was conducted to assess and rank the relative influences of different traffic parameters on emissions. This was achieved through a literature review, and through the processing of existing data.

(iii) *A review of sensitivity analysis studies*. An in-depth analysis of the COPERT methodology, including the identification of sources of uncertainty, was also conducted. Furthermore, a range of factors relating to traffic data requirements, user expectations and modelling difficulties were considered.

(iv) *The classification of road traffic in ARTEMIS*. This involved the collection, processing, assessment and application of existing national road traffic data in Europe, including information on traffic activity, trip lengths, engine temperatures, speeds, driving patterns and traffic composition. The results helped to define the ARTEMIS emission model for road transport, and provided direct inputs into it. A ‘traffic situation’ modelling approach was defined for use in ARTEMIS, as well as a conventional average-speed approach (see Section B3). This required the characterisation of driving patterns corresponding to a range of traffic situations.

B2.2 Review of existing information on road traffic characteristics

In COST319 and MEET various activities were conducted to determine the types of traffic information required for modelling, what was actually available, and whether the available data were compatible with modelling objectives (André *et al*., 1999). Significant differences were apparent between the information required and the information available. The main conclusions from these activities were:

(i) The road traffic statistics required for emission modelling represent a large field of investigation, but it is often difficult to obtain reliable and consistent information. Problems include country-specific particularities such as differences in language, methods and data, heterogeneity of sources, and incomplete statistics.

(ii) There are significant weaknesses - and hence high levels of uncertainty - in the data, particularly in relation to driving conditions, gradient, altitude, vehicle load, engine operation and spatial information on traffic.

(iii) The heterogeneity and variability of driving and usage conditions, and the influence of numerous factors, has raised the question of the robustness of the data (André and Hammarström, 2000).

(iv) International statistics are not always the most reliable, and should be used with caution when estimating emissions.

The initial objective of ARTEMIS was to collect and integrate data on traffic characteristics and activity in order to reduce discrepancies between emission estimates made in different ways. However, before determining the data requirements in detail, a number of different aspects were considered. These are summarised below.

B2.2.1 User expectations in relation to traffic data

International users, such as the European Commission, expect the traffic data used in emission models to be harmonised, already in widespread use, appropriate for forecasting, and consistent with national published transport statistics. Work in projects such as TERM[8] has demonstrated the need for consistency in the European statistics system. Users who are modelling at the national level will expect tools which are compatible with their existing modelling approaches, and with their methods of analysing transport and traffic data. It is likely that such users would also appreciate traffic data which are consistent with published statistics. Other users, such as consultants and non-specialist researchers, would expect reliable traffic data, and would need to be able to understand its validity and the underlying assumptions. However, depending on the actual user and application, expectations could vary a great deal. In summary, traffic data should be reliable, accurate, consistent and available for different countries. Clear information on validity and any assumptions made is also important.

B2.2.2 Modelling practices

MEET and COPERT are two of the most widely used emission models in Europe. These models include both emission functions and national traffic data sets for European countries. However, the data sets have not been updated, and although such common methods are available several European countries use their own methods of estimation. Some use the COPERT emission factors, but not the traffic data or structures provided, and compute traffic data (activity, vehicle fleet, speed, *etc.*) in different ways. In most cases, a national data set is periodically developed, but the data may not be available for other users. Furthermore, the diversity of the national institutions responsible for transport, the environment and statistics render the understanding of these complex mechanisms rather difficult on a European scale. It is also important to note that there are substantial differences in the input data structure of different applications (Urquiza, 2003; Adra and André, 2005a). For example, European tools do not include clear recommendations on how to deal with traffic data for different types and scales of application. In addition, the structures and definitions of traffic in models are often incompatible with the types of data which are available to the user. In such cases, users must make assumptions and adapt their data; the need to balance estimated fuel consumption and the amount of fuel sold can lead to arbitrary adjustments being made to input data. For these reasons large discrepancies can be observed between different estimates, even where comparable assumptions are used. The inter-comparison exercise conducted in France by Lacour (2002) clearly highlighted this problem.

B2.2.3 Reliability of traffic data

Significant differences between the MEET/COPERT traffic statistics and published national data were observed by Zachariadis and Samaras (2001), based upon total vehicles-kilometres travelled (**Table B2-1**). For the EU15 the values for passenger cars and goods vehicles differed by 12% and 37% respectively. The differences for some individual countries were much higher, reaching 20-40% for passenger cars and 200-400% for HDVs.

Table B2-1: Example of differences in the total vehicles-kilometres estimated from MEET/ COPERT and from European official statistics (Zachariadis and Samaras, 2001).

Country	Difference in the total vehicle-kilometres per country (negative values indicate where MEET was lower than the official statistics). Blank spaces indicate that the difference was not significant (<15%).	
	Cars	Goods vehicles
EU 15	-12%	+37%
Belgium	+17%	+433%
Denmark		+32%
Finland	-41%	
France	-19%	+23%
Italy	-24%	+45%
Luxembourg		+222%
The Netherlands	-24%	
Portugal		-34%
Sweden	-20%	+211%
Spain		+210%

[8] TERM: Towards a transport and environment reporting mechanism (TERM) for the EU. Project managed by the European Environment Agency in co-operation with EUROSTAT.

Such differences are not acceptable, and are incompatible with the objectives of assessing the environmental policies of the member states, or comparing modes, countries, *etc*. The impacts of such gaps on emission estimates are likely to be much more important than other sources of uncertainty. There is clearly a need for traffic data which concur with official statistics, at least for inventory purposes. As well as total vehicle-kilometres travelled, other traffic statistics probably ought to be viewed with caution. For example, the speed values in MEET/COPERT appear to be significantly overestimated for around half of the countries in Europe (André and Hammarström, 2000), and the geographical distribution of traffic (urban, rural and motorway) seems to be quite arbitrary.

B2.2.4 Conclusions and recommendations

Conclusions

The crucial role of traffic data in emission modelling has generally been neglected. The diverse objectives of emission modelling, the complex practices involved, the large range of traffic data required, and the weaknesses, inconsistencies and gaps in the data all combine to make the task rather difficult. Close and efficient co-operation between emission modellers and traffic experts, and the strong involvement of national institutions, are necessary to provide more direct links between traffic data and emissions factors, to define appropriate model parameters according to existing statistics and user needs, and to define a modelling framework which could gain international acceptance. Gaps in official data, such as those mentioned above, are not acceptable for emission modelling, and the value of the traffic data in MEET/COPERT is questionable. Reasons for this include (i) their reliability is considered to be poor, (ii) they are not widely used and (iii) they may be used inappropriately.

Recommendations

Definition and construction of a traffic data set

Regarding the provision of traffic data for use in European models, the following recommendations are made:

(i) Information relating to traffic data sets must be clear and transparent. Actual data, default data, and estimated data should be clearly identified. Any assumptions and information on validity should also be documented.

(ii) National traffic data for use in emission inventories should be collected using an official and systematic procedure, preferably with the co-operation of EUROSTAT.

(iii) Traffic-related parameters for which no data are available to users should not be required by emission models. Conversely, any input data which are required for emission modelling should be available to users, at least at the national level and on a yearly basis.

(iv) The most appropriate types and formats of data and statistics should be identified. The use of short-term traffic data should be avoided where possible.

(v) Official national transport and traffic statistics should be compiled in a manner which is relevant for use in emission models.

(vi) Statistics should be limited to the national level, as detailed spatial disaggregation is often impractical.

Inter-disciplinary co-operation

(vii) The traffic characteristics required for use in an emission model depend upon the model structure, and experts from several different disciplines are required in the overall process. Close co-operation between experts in vehicle emissions, modelling and traffic is clearly required.

(viii) The traffic data for different vehicle categories need to be consistent. For example, the same definitions of traffic situations must be applicable to cars, heavy-duty vehicles, and two-wheel vehicles.

(ix) The road traffic characteristics and data used for emission estimation rely firstly on the identification of the traffic-related factors having a significant impact on emissions. These factors are generally determined from a technical viewpoint - in other words their influence on emissions - and not usually from the traffic viewpoint. This situation probably ought to be reversed.

(x) More emphasis should be placed upon user needs during the model design phase. This requires close interaction with model users.

(xi) There are currently wide disparities between the types of traffic statistics compiled by different countries. An efficient co-operative process is required to establish internationally agreed definitions and structures for a framework of traffic data. Different countries should then be encouraged to adopt this agreed approach for the compilation of their national statistics.

B2.2.5 ARTEMIS objectives in relation to traffic data

In ARTEMIS, the aim was to collect, process and apply existing data relating to fleets, usage and driving conditions for road vehicles in EU and CEEC countries, as required for the estimation of emissions. At this stage, it is useful to distinguish between two types of data:

(i) *Input data* which are required of the user for the estimation of emissions for a particular case study (typically traffic volume, composition, speed).

(ii) *Built-in* or *internal data* which are required inside the model. These data are generally not known by users and should not be entered by them (*e.g.* speed profiles).

It was not possible in ARTEMIS to provide a whole set of traffic-related statistics for each of the EU and CEEC countries, and in any case users are generally responsible for the input data corresponding to a particular application. The following tasks were considered to be the priorities:

(i) *Identification of the traffic parameters and the structure for emissions estimation*. This was required to identify the most important issues regarding traffic characteristics for use in emission models, and to select, define and structure the input traffic factors/data to be consistent with these statistics.

(ii) *Identification and management of traffic data*. The sources of traffic data were identified, and the validity of the data was assessed. The definition, structure and accuracy of existing transport statistics in relation to their use in emission modelling were also considered.

(iii) *Collection of 'input' and 'built-in' traffic data*. Input data and built-in data were collected and processed where possible.

B2.3 Traffic data requirements

This Section reviews the traffic data requirements for emission modelling. The basic requirements of emission models, model-related aspects, and the understanding of the different types of emission source are considered.

B2.3.1 Basic definitions and requirements

In the simplest terms, the total emission of a given pollutant from a road traffic source is calculated as the product of a specific emission factor and a quantity of traffic activity:

$$\boldsymbol{E = e \cdot T} \qquad \text{(Equation B2-1)}$$

where: $\boldsymbol{E}$ = total emission
$\boldsymbol{e}$ = emission factor
$\boldsymbol{T}$ = road traffic activity

However, several different sources or processes need to be considered. The principal sources are 'hot' exhaust emissions, cold-start exhaust emissions and emissions due to the fuel evaporation. For particulate matter, abrasion processes such as tyre wear, brake wear and road surface wear should also be considered. The emission factor may be expressed in terms of distance travelled (*e.g.* hot emissions), per vehicle start (*e.g.* excess emissions due to cold start), or per unit of time (*e.g.* evaporative emissions), and there is a need to state Equation B2-1 accordingly. As the emission factor varies according to, for example, vehicle type, vehicle technology and vehicle size, such factors also need to be considered, and then the traffic volume distribution needs to be determined as a function of these factors. The vehicle operating condition – and therefore the emission factor - varies as a function of the geographical area (urban, rural), the road configuration (urban street to motorway) and the time period. There is also therefore a need to define the equation according to such considerations, or alternatively according to generalised traffic situations, and then again to obtain the traffic volume distribution. As the emission factor is also a function of the various operating conditions, a second set of parameters is required to describe these operating conditions. For the prediction of future emissions, traffic forecast information is required.

Road traffic volume and fleet structure

Road traffic volume (or flow) is a fundamental user input, and should be stated in vehicle-kilometres. Alternatively, numbers of vehicles and their corresponding annual mileages, or the number of vehicles on a given length of road, can be used. The traffic must then be disaggregated according to pre-defined categories (*e.g.* light-duty vehicles, heavy-duty vehicles, two-wheel vehicles), a process which requires the definition of a classification system. It is necessary to ensure that such a system can be applied in every country. The second level of this structure involves a more detailed classification in terms of fuel use (*e.g.* petrol, diesel, LPG), engine and exhaust technology (direct injection, catalyst, particulate filter, *etc.*), and emission standard. This structure has to be defined by emissions experts, taking into account which technological parameters have a significant influence on emissions. The effects of auxiliary devices should also be considered. Finally, vehicle age is also an important factor affecting emissions. Taking into account the above structure, it is necessary to quantify traffic volume and its distribution. Unfortunately, when the fleet structure is rather complex such data cannot be readily measured, and modelling of the vehicle fleet is then required. Fleet models are typically based on numbers of registrations, annual mileage distributions, and assumptions concerning the lifetimes of the vehicles (survival coefficients or curves). However, the survival coefficients are a weak element of models, as there are few supporting data.

Traffic situations

Traffic situations reflect various aspects of road transport activity, including:

(i) The geographical structure (urban, suburban, rural, *etc.*).

(ii) The road characteristics (motorways, number of lanes, sinuosity, gradient, *etc*.),

(iii) Temporal aspects (peak / off-peak hours, day / night traffic, week / week-end, holidays, *etc)*.

(iv) Climatic conditions (temperature, humidity, wind speed, *etc*.),

(v) Other traffic conditions (congested, free-flowing, *etc*.).

Obviously, some of these characteristics overlap. However it is possible that the structures envisaged in the past were not totally coherent. For instance, the classical 'urban/rural/motorway' structure mixed geographical and road considerations.

Operating conditions

In MEET/COST319, it was concluded that emission factors are strongly influenced by the vehicle category, type of road, mean speed or driving pattern, road gradient, vehicle load, and emission deterioration factor (linked to the vehicle age or mileage). Cold-start emissions depend upon ambient temperature, engine temperature at the start of a trip, trip length, mean speed and vehicle technology and type. Evaporative emissions depend on trip length distribution, ambient temperature, fuel volatility and vehicle technology. A definitive list of these influencing operating conditions had to be established via discussions with experts on emissions.

B2.3.2 User-related and model-related aspects

The user-related and model-related aspects of model development were investigated by Keller *et al*. (2001). The conclusions from this work are summarised below.

Level of application

Different model users need to estimate emissions on different spatial scales and for different types of application. Types of application can be classified according to the spatial scale (from the local to the national), or alternatively according to their purpose. Typical applications include:

(i) 'Classical' emission inventories at different levels of spatial resolution, from national down to regional (and city) level, and including scenarios (*e.g*. impacts of changes in fuel quality, emission standard). The driving forces are reporting mechanisms and regulation.

(ii) The evaluation of programmes (*e.g.* strategic environmental impact assessment), projects and measures, from regional action plans to individual measures like traffic management.

(iii) Inputs for air quality models, which can essentially be considered as an expansion of the emission calculations.

Whilst the first type of application can be undertaken at an aggregated level (macro-scale), the second and third types often require street-level (micro-scale) estimations. The distinction between macro- and micro-scales has implications for the definition of input parameters, as well as the needs in terms of traffic data.

Input data versus user data

In relation to data which should form part of the model itself, and data which should be the responsibility of the user, it was concluded that:

(i) Users have a good knowledge of the traffic activity data relating to their own case studies. It is therefore not necessary to provide the traffic activity data, but the data structure does need to be defined.

(ii) The detailed vehicle fleet composition is generally not known by users. Fleet composition information is therefore required for EU Members States and for years between 1980 and 2020.

(iii) Traffic activity data should be managed as both vehicle-km in a given area (for macroscopic applications) and as number of vehicles per road section (for microscopic applications). Traffic activity may be adjusted taking into account external data (*e.g*. official transport statistics).

Structural aspects

In the context of the structural aspects of the emissions calculation, it was proposed that:

(i) Traffic activity should be broken down into vehicle categories and traffic situations or operational conditions. Vehicle and traffic classifications need to be flexible and adaptable.

(ii) Traffic situations may include geographical aspects (urban/rural, road type) and temporal aspects (*e.g.* level of congestion as a function of the time-of-day). Traffic situations have to be common for the different road transport modes, and they should be defined with reference to effects on emissions and the availability of data.

(iii) The fleet composition (per vehicle segment) is the combination of the number of vehicles, their annual mileage, their age distribution, correction factors for vehicle age, and assumptions regarding the introduction of new technological concepts. Various fleet compositions can occur for different traffic situations.

(iv) Although the traffic activity should be left to the user to define, the prediction of future levels of activity and fleet turnover can be included in the model itself. Appropriate methods include the one used in MEET (modelling of the evolution of vehicle numbers and survival rates), or one based only on vehicle age distributions.

Operational aspects / driving conditions

Keller *et al.* (2001) stated that traffic situations should be described by driving conditions. These should be defined in terms of average speed and dynamic parameters for typical speed profiles. This implies a correlation between speed on one hand, and traffic situations or road classifications on the other. Load factors, engine starts and parking conditions can be seen as specific operational conditions. The understanding of these situations, as well as other factors such as emission degradation as a function of mileage, the influence of inspection and maintenance, the effects of the road gradient, and the effects of vehicle air conditioning, should be improved.

B2.3.3 Detailed requirements

An enquiry was conducted to determine modelling requirements in terms of traffic-related parameters, and the results are summarised in **Tables B2-2** and **B2-3**. Although incomplete, these results formed the basis for the traffic data and input parameter requirements in ARTEMIS. The values of most of these parameters evolve with the time. This evolution is, however, not easy to take into account. The light commercial vehicle category includes vehicles which are similar to passenger cars as regards their engine technology. The usage of such vehicles is, however, very specific, and this justifies a separate modelling approach. It could be advantageous to consider emerging or specific vehicle categories such as SUVs (sports utility vehicles), vans, four-wheel-drive vehicles, as well as the types of vehicle in Central and Eastern European countries. Specific operating conditions should also be considered. For the estimation of emissions due to cold starts, evaporation, and the use of air conditioning, similarities in the thermal and vehicle use parameters (ambient temperature, trip length, *etc*.) should be investigated.

B2.4 A review of sensitivity analysis studies

Several sensitivity analyses were conducted within, or in conjunction with, ARTEMIS. These studies identified the parameters which need to be accurately defined in order to produce reliable estimates of emissions. Similar exercises have been conducted using the US MOBILE and EMFAC7G models (Pollack *et al*. 1999; Frey *et al*. 1999), but ARTEMIS focused on the main results and conclusions from European work. Most of this work was conducted by applying the COPERT model to specific national or local case studies.

A study by SCM/EMITRA (2001) examined the sensitivity of emission estimates to traffic parameters for the road network in Lyon. The EMITRA model combined origin/destination matrices with a traffic assignment model and the COPERT II emission functions. The emission uncertainty for passenger cars was of the order of 20-30% for a variation of 20% in the input parameters, but was found to be higher for heavy-duty vehicles. The main parameters affecting variability were traffic flow (60%) and speed (30%). These two parameters accounted for around 90% of the total variability, except for evaporative emissions which were dependent upon fuel volatility (30%) and traffic flow/speed (60%). However, the work did not consider the uncertainty in the emission factors themselves.

Duboudin and Crozat (2002) analysed of the sources of uncertainty within COPERT III. The analyses were conducted for (i) a single urban road section and (ii) a national inventory for France. The variations in the input (external) and emissions (internal) parameters were defined according to the scientific knowledge. For the urban road study, the most important external parameters were found to be traffic flow, speed, the percentage of distance driven with a cold engine and the petrol:diesel ratio (this list varied according to the pollutant). The main internal parameters were the cold-start excess emission and emissions from non-catalyst petrol cars. The main parameters for VOCs were the emission factors for HDVs, two-wheel vehicles and non-catalyst petrol cars. The analysis revealed an uncertainty on the total emission in the range of ±15% to ±25%, depending on the pollutant (except CO_2). Internal and external parameters appeared to be equally important. In the French national inventory case study, the uncertainties on the total emissions were found to be in the range of ±20% to ±35% for CO and HC, ±13% to ±20% for NO_x and PM, and ±12% for CO_2. When an adjustment for actual fuel sales was applied, this led to an improvement in the overall accuracy. The authors concluded that the uncertainty was linked to internal and input parameters, the most important being (i) traffic volume (ii) speed (iii) the hot emission factors for non-catalyst petrol cars (iv) the cold-start excess emission and (v) for PM and NO_x the diesel car and HDV emission factors.

Table B2-2: Traffic data requirements for the modelling of hot emissions (PC = passenger car, HDV = heavy-duty vehicle).

Parameter type	Parameters in the emissions calculation	Data form
Vehicle category	-Fuel: petrol, diesel, *etc*. -Standard: pre-Euro, Euro I, *etc.* and age -Engine capacity and technology (PC) -Vehicle size/weight (HDV) -After-treatment (catalyst, filter, *etc*.) -Vehicle type (*e.g.* vans, 4x4) -Vehicles in Central & Eastern European countries should be treated separately	-Number of vehicles per year and per segment
Activity level	-Mileage per vehicle segment	-Annual mileage of vehicles per segment -Evolution of annual mileage as a function of vehicle age
Driving conditions	-Activity distribution for different traffic situations	-Distributions of mileage for different traffic situations
	-Vehicle driving and operating conditions	-Driving conditions (speed patterns, average speeds) and distance travelled for each traffic situation and per vehicle segment
	-Gradient (HDV)	-Driving conditions and distance travelled by gradient for each traffic situation and per vehicle -Macroscopic indicators of gradient and curvature could be considered for large scales of application
Other operating conditions	-Load factors (HDV)	-Driving conditions and distance travelled for typical load factors and empty running, for each traffic situation and detailed vehicle segment -Load factors and empty running vary according to the time, to the vehicle age and to the vehicle category
	-Ambient weather conditions (temperature, humidity, altitude, pressure)	-Typical annual, daily distribution(s) per country
	-Fuel characteristics	-Distribution of fuel sales according to fuel specification -Fuel specifications per country -Should be consistent for vehicle categories

Table B2-3: Traffic data requirements for the modelling of cold-start, evaporative and air conditioning (A/C) emissions (Passenger cars, light duty vehicles).

Parameter type	Parameters in the emissions calculation	Data form	Remarks
Vehicles concerned	-As hot emissions + specific equipment	-% of vehicle equipped per segment	Other technical specifications could be needed, such as canister equipment for the control of evaporative emissions, and A/C equipment.
Activity level	-Number of starts -Duration of parking -Duration of driving -Trip number -A/C operation	-Numbers of cold starts and trips -% of driving with A/C on.	
Driving conditions	-During the cold-start phase -During the AC operation	-Detailed knowledge of speeds and driving conditions.	Cold-start, air conditioning and evaporative emissions should be influenced by the driving conditions
Other operating conditions	-Trip length -Ambient and local weather conditions -Engine temperature at trip start and at trip end. -Parking conditions	-Typical trip length, distribution or average values. -Typical annual, daily temperature distribution(s) per country. -Distribution of the minimum and maximum daily temperatures (per country)	For A/C, the level of operation, the initial cooling after a trip start and the stabilised operation should be considered
	-Fuel characteristics	-As hot emissions	Density, volatility should be considered for the evaporative emissions

Within ARTEMIS, Kioutsioukis and Tarentola (2003) conducted a literature review and analysed the uncertainty in emission estimates in relation to (i) a single rural road (in a tunnel) and (ii) two national inventories (Italy and France). Again, the COPERT III model was used, and a Monte-Carlo simulation approach was applied. At the road level, the speed and the load factor for HDVs were generally found to be the most important parameters, and accounted for up to 70-80% of the variability in emissions. For the national inventories, the following main parameters were identified: trip length (used to compute the cold-start emission), the petrol:diesel ratio, the annual mileage, the urban speed and the urban mileage share for passenger cars. The emission factors also played a major role for NO_x, a secondary role for VOC and PM, but no role at all for CO_2.

For the UK, a range of simulations were conduced by Cloke *et al.* (2001) to quantify the effects of the following parameters: (i) vehicle distributions and categorisation (ii) speed (iii) vehicle age (iv) trip length and (v) ambient temperature. The results demonstrated the importance of speed, HDV weight, and the PC age/legislation category. The authors recommended that these parameters (in particular speed and fleet composition) should be quantified more accurately for local-scale studies.

These sensitivity studies highlighted the importance of accurate data for several traffic parameters, notably traffic flow, annual mileage and speed, which are generally more important than the actual unit emission factors. This raises the question of the quality of emission estimates, as most effort is usually dedicated to the measurement and modelling of emissions, whilst the quality of the necessary traffic data is rarely considered.

B2.5 Development of the ARTEMIS traffic situation model

In Section B2.4 sensitivity studies indicated the relative importance of different road traffic parameters in the estimation of emissions. The remaining aims of the model development work in ARTEMIS were:

(i) To interpret modelling requirements in terms of these traffic parameters, their exact definitions, their structure, *etc*.

(ii) To collect the required road traffic data, including information on vehicle usage, driving conditions, speeds, vehicle fleets and traffic activity. The initial objective was to construct datasets at the national level.

Emission estimates are often required on a small spatial scale, such as for a single street. Pollutant emissions are generally sensitive to different ‘traffic situations’, as driving conditions can vary significantly. Furthermore, population exposure is linked spatially to the emission source. However, existing emission models are not generally designed for such applications. In previous European approaches (European Commission, 1999), the traffic classification structure was not detailed enough for certain applications. A more detailed structure was used in the Handbook (Keller *et al*. 1995), whereby traffic situations were defined as a combination of road and traffic parameters. The traffic situation approach was therefore considered necessary in the ARTEMIS model, and this led to a number of complications:

(i) In this type of modelling approach, the traffic situation scheme (the system of classifying traffic) forms the basis of the emission calculation. It is necessary to define a structure which can be applied consistently in different countries. The classification system should preferably be similar to that used by transport and traffic engineers, but should also be meaningful in terms of emissions. It should be detailed, clearly-defined, understandable, unambiguous, well-documented and, where possible, close to the definitions already in use.

(ii) It is then necessary to develop approaches for estimating pollutant emissions at this level. However, the relationships between detailed driving conditions and pollutant emissions are not well-defined, apart from a simple dependency on average speed. No clear relationships with other kinematic parameters have been established.

(iii) A detailed structure implies a need for extensive data to cover all traffic situations.

The work would have achieved these objectives in full, but the efficiency of the data collection exercise was quite low due to problems of access and the difficulty of involving the relevant institutions in a process which appeared to be very complex and time consuming. The most significant results of the exercise were the following:

(i) The vehicle fleet structure was defined.

(ii) A traffic situation scheme was designed, taking into account the above considerations (Poize, 2002; André and Poize, 2002; Keller and De Haan, 2003; Fantozzi *et al*., 2005; André *et al.*, 2006). Approaches were developed for estimating emission factors for each traffic situation, including the identification of relevant driving patterns (Fantozzi *et al*., 2005, André *et al*., 2006; André and Fantozzi, 2005).

(iii) A review of existing traffic data was undertaken. Load factors, annual mileages, trip characteristics, vehicle survival rates, fuel characteristics and speeds were covered. Although this work did not lead to data and functions directly applicable within the ARTEMIS model, the summary of the state-of-the-art helped in the construction of default datasets for the model. A specific investigation into traffic data for Central and Eastern European countries was also conducted.

The results are summarised in the following paragraphs.

B2.5.1 Vehicle classification

The system of classification for road vehicles which was designed for use in the ARTEMIS road transport model is given in **Table B2-4**.

Table B2-4: Fleet structure in ARTEMIS road transport model.

Category	Sub-category
Passenger car	Engine capacity < 1.4 litres
	Engine capacity 1.4-2.0 litres
	Engine capacity > 2.0 litres
	SUVs (>2.0 litres)
	Two-stroke engines (Eastern Europe)
	Four-stroke engines (Eastern Europe)
	Not specified
Light commercial vehicle	M and N1-I
	N1-II
	N1-III
	Not specified
Heavy-duty vehicle	Rigid truck, gross weight <=7.5 tonnes
	Rigid truck, gross weight >7.5-12 tonnes
	Rigid truck, gross weight >12-14 tonnes
	Rigid truck, gross weight >14-20 tonnes
	Rigid truck, gross weight >20-26 tonnes
	Rigid truck, gross weight >26-28 tonnes
	Rigid truck, gross weight >28-32 tonnes
	Rigid truck, gross weight >32 tonnes
	Rigid truck, not specified
	Articulated truck, gross weight <=7.5 tonnes
	Articulated truck, gross weight >20-28 tonnes
	Articulated truck, gross weight >28-34 tonnes
	Articulated truck, gross weight >34-40 tonnes
	Articulated truck, gross weight >40-50 tonnes
	Articulated truck, gross weight >50-60 tonnes
	Articulated truck, gross weight >60 tonnes
	Articulated truck, not specified
Coach	Gross weight <=18 tonnes
	Gross weight >18 tonnes
	Gross weight not specified
Urban bus	Gross weight <15 tonnes
	Gross weight 15-18 tonnes
	Gross weight >18 tonnes
	Gross weight not specified
Motorcycles	Engine capacity <=50cc
	Engine capacity <=150cc
	Engine capacity >150cc
	Engine capacity 151-250cc
	Engine capacity 251-750cc
	Engine capacity >750cc
	Engine capacity not specified

B2.5.2 Definition of traffic situations

The structure of a traffic situation scheme should relate to the traffic parameters which influence emissions. For example, vehicle kinematics and engine operation are directly influenced by the road characteristics, including the width of the lanes, sinuosity, gradient, speed limit, and the presence of junctions, as well as by the traffic conditions. Other parameters, such as usage, behaviour, and climatic conditions, can be viewed as being external, more difficult to assess in the context of a street-level calculation, more difficult for the user to address, and possibly of less importance regarding emissions. These parameters would generally be managed at a larger scale through the used of average values.

Assuming that the analysts responsible for estimating pollutant emissions at the street level work closely with traffic engineers, it seems appropriate to employ a system of road classification which is already in use. Road classifications generally distinguish between urban and rural situations, and address various objectives (safety, traffic management, *etc*.). Functional classifications (*e.g.* 'access road', 'distributor', 'through road') are commonly used. Other characteristics are often associated, or derived from, the functional class, such as the area type, the number of lanes, the speed limit, numbers and types of junction, parking areas, and transport modes.

The definitions of 'urban' and 'rural' should be consistent, but are often subject to debate. Indeed, many different national definitions have been reported (UN, 2001)[9]. Some studies promote the adoption of a 'functional' definition (SPESP, 2000), or a 'morphological' approach (Le Gléau *et al*., 1997). Indeed, the city, the traffic, the road network and its hierarchy are generally managed in this way by the relevant authorities. Furthermore, travel and traffic conditions are closely linked to these structural aspects. The main implication of using such approaches is that villages and small towns that are isolated in a rural context are considered as rural, whilst there can be villages and even rural territories within an urban area.

Road classification

The analysis of actual practices led to a road classification system for ARTEMIS which was based primarily on road function and the hierarchical organisation of the road network (Lhuillier, 2004). Road characteristics, such as lane width, parking, junction type and junction density, are generally linked to these functions. The distinction between motorways and normal roads having the same function is rather important, because this implies a significant difference in driving patterns. The classification system is shown in **Table B2-5** and **Table B2-6**. This system is similar to existing classifications. Obviously, local specificities and exceptions can occur, but these cannot be taken into account in this context.

Table B2-5: ARTEMIS classification for urban roads.

Main function	Comments	Code	Speed limit (km/h)
National and regional network	High-speed or major roads carrying regional or national traffic through urban areas.	5a: Motorway	80 - 130
		5b: Non-motorway	70 - 100
Agglomeration, primary network	High-speed or major roads in urban areas, with rapid exchanges at the city level. Primary distributors, primary roads.	4a: Motorway (*e.g.* ring road)	60 - 110
		4b: Non-motorway	50 – 90
District distributor roads	Provide connections between districts or 'poles', and access to and from primary distributors.	3: Road	50 - 80
Local distributor roads	Connections between communities and within districts. Access to and from district distributors, inner exchange roads and local roads.	2: Road	50 – 60
Access roads	Local roads which provide access to residential and commercial areas.	1 - Road, cul-de-sac, side road	30 - 50

Table B2-6: ARTEMIS classification for rural roads.

Main function	Comments	Code	Speed limit (km/h)
National and regional network	High-speed or major roads carrying regional or national traffic through rural areas. Connections between villages and towns.	5 - Motorway	80 - 150
		4 - Trunk road	60 - 110
Distributor roads	Connections between villages and towns, and access to and from the national or regional network.	3 - Road	50 - 100
Local distributor roads	Roads through villages, and occasional access to properties such as farms. Inner exchange roads and local roads.	2 - Road	50 - 80
Access roads	Access to properties, residential roads.	1 - Road, cul-de-sac, side road	30 - 50

[9] Work by the United Nations has demonstrated the difficulty of defining the meaning of 'urban'. Example definitions include 'a city of about 1,000 inhabitants' (Albania), 'a city with more than 80,000 inhabitants' (Sweden), an area 'for which the distance to an administrative office is less than 7 km' (Cyprus), an area 'of high density of activity' (Netherlands), and an area 'in which the speed limit is 50 km/h' (Turkey).

Sinuosity and gradient

In addition to the road types defined in **Table B2-5** and **B2-6**, two complementary parameters must be considered: the road gradient (due to its strong effect on HDV emissions and fuel consumption), and sinuosity (which has a strong effect on driving conditions in rural areas). These two parameters are linked, as sinuosity is generally observed in mountainous areas, and large gradients usually imply a high degree of sinuosity (André and Fantozzi, 2005). The ARTEMIS classifications for gradient and sinuosity are defined in **Table B2-7**.

Table B2-7: ARTEMIS classification of gradient and sinuosity.

	Type	Comment
1	Flat and non-sinuous	Low sinuosity without incidence on the speed
2	Hilly straight roads	Long ramp on main roads and motorways
3	Hilly and sinuous	
4	Mountainous and strongly sinuous	of which the Alps particular case

For national or regional emission estimates, a qualitative approach is proposed, based upon macroscopic quantitative indicators, such as the sum of successive angle changes per kilometre in radians/km, or the sum of changes in height in m/km, as proposed by Bjorketun (2003). Indeed, the gradient alone would have no meaning on a large scale. For very local estimations, the inclusion of local gradients remains a challenge, as it would require a large quantity of information, including driving data for each gradient.

Traffic conditions

A review of existing descriptors for traffic conditions has indicated a general lack of consistency in the terminology used (André and Fantozzi, 2005). It appeared also that the worst conditions (level of service F) defined in the widely-used US Highway Capacity Manual (HCM) (TRB, 2000), or the equivalent in other classifications - with ranges in speed of the order of 50% of the free-flow speed, and traffic densities of around 30 vehicles/km/lane - were somewhat removed from typical ‘stop-and-go’ traffic conditions.

For a good level of coverage of actual traffic conditions, a four-level structure in four was proposed (**Figure B2-1** and **Table B2-8**), with ‘free-flow traffic’ corresponding to the levels A and B of the HCM (an average speed between 85% and 100% of the free-flow speed), ‘heavy traffic’ corresponding to the levels C and D of the HCM (with a constraint speed between 65% and 85% of the free-flow speed), ‘unsteady quasi-saturated traffic’ corresponding to level E (or higher) of the HCM (with variable speed and possible stops in the range of 30% to 60% of the free-flow speed), and finally ‘stop-and-go traffic’ (with a speed below, or in the range of, 10 km/h).

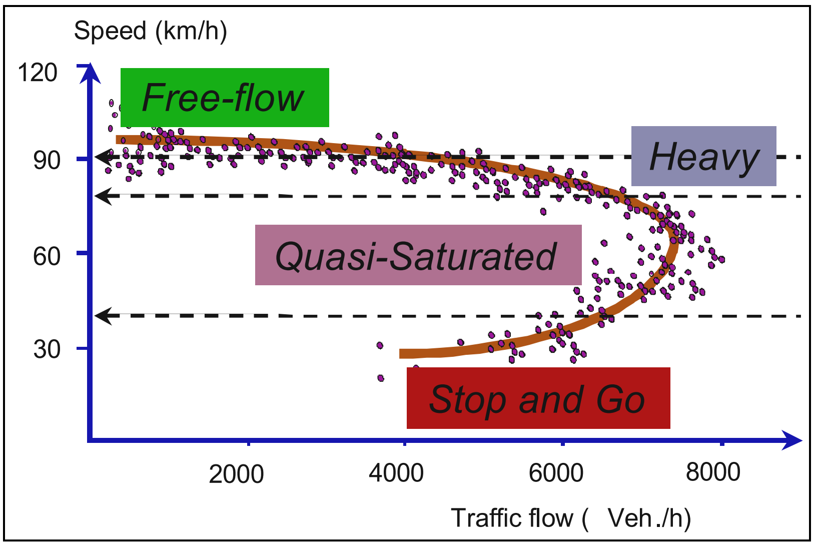

Figure B2-1: Four levels of service according to speed and traffic capacity (Lhuillier, 2004).

Table B2-9: Traffic conditions and illustrative speed range for two contrasting road cases.

Traffic level and conditions		Indicative speed range (km/h)	
		Motorway, 110 km/h	Road, 50 km/h
1	Free-flow conditions, low and steady traffic flow. Constant and relatively high speed.	90 - 120	45 - 60
2	Free-flow with heavy traffic. Constrained but relatively constant speed.	70 – 90	30 - 45
3	Heavy and unsteady flow, quite saturated traffic. Variable intermediate speeds with possible stops.	30 – 70	15 - 30
4	Stop-and-go, heavily congested flow, or gridlock. Variable and low speed and stops.	5 - 30	5 - 15

Traffic situations scheme

The combination of the above parameters resulted in a complete traffic situation scheme which included no less than 474 traffic situations, covering the road type, the usual speed limit, the traffic conditions in four classes, and the gradient and sinuosity in four classes (for rural areas only). An example of a simplified grid of 276 traffic situations for passenger cars (with the gradient not included) is shown in **Table B2-10**. Speed data are also given. The 69 traffic situation for which speed data were available, and the 19 additional traffic situations corresponding to each of the ARTEMIS driving cycles or sub-cycles, are described in Section B3.43. Similar grids were defined for heavy-duty vehicles, buses and motorcycles. Although this highly detailed structure provides a reasonably accurate means of describing driving conditions for a large range of emission estimation exercises, it raises the difficult question of whether users will be willing and able to provide appropriate and reliable input data, such as speed and mileage distributions.

B2.5.3 Method for assessing traffic situation emissions

Representative speed data

Representative speed data were required to characterise each traffic situation. For cars, existing driving data were collected from the ARTEMIS partners, providing that it was well documented, in order to allocate a speed-time profile to each of the traffic situations. A complementary experiment was conducted to monitor one car in a certain number of cases clearly identified by the traffic situation scheme, including hilly and mountainous roads. In all, more than 1,500 speed-time profiles were collected, but usually the information on the traffic conditions was not available. However, very few data were available for rural and for hilly and mountainous situations. The available speed data were allocated to the different traffic situations according to the driving parameters (average speed, frequency of stops *etc.*). However, this process enabled the coverage of only 70 of the 400 or so defined cases. In fact, it was possible to fill in the missing data via direct linkages between ‘similar’ traffic situations. An equivalent process which was conducted for heavy vehicles and two-wheel vehicles led to similar conclusions.

Although an extensive dataset is summarised in **Table B2-10**, there remained a certain number of inconsistencies (*e.g.* heavy-duty vehicle speeds which were higher than those for cars within the same traffic situation). Further work is required to resolve such issues and to record data for the situations for which no data exist.

Emission factors

The ARTEMIS driving cycles for passenger cars (see Section B3) were designed to describe European driving conditions in their diversity, thus allowing a detailed analysis of emissions in terms of kinematic parameters. However, the emissions data collected in ARTEMIS also concerned a large range of non-ARTEMIS driving cycles. The analysis of these cycles led to the development of a cycle classification scheme which was used to define emission factors for specific traffic situations for use in the ARTEMIS model (André, 2004a, 2004b). Again, this work is described in more detail in Section B3. Similar work was conducted for heavy-duty vehicles (Sturm *et al.,* 2006) and two-wheel vehicles (Elst *et al.,* 2006).

The lack of appropriate speed-time profiles, or their poor quality, remains the main limitation and weakness of the traffic situation approach. For the time being, such an approach should be reserved for local applications, whilst regional or national inventories should rely on a more macroscopic and robust approach. However, the conceptual framework is effectively operational and ready to accept new data.

Table B2-10: Traffic situations and speed data - passenger cars.

Area		Road type		Level of service		Average speed by speed limit (km/h)											
						30	40	50	60	70	80	90	100	110	120	130	130+
1	Rural	10	Motorway	1	Free-flow						74	80	94	100	118	122	152
1	Rural	10	Motorway	2	Heavy						72	72	74	74	90	90	90
1	Rural	10	Motorway	3	Saturated						31	31	31	31	31	31	31
1	Rural	10	Motorway	4	Stop-&-go						23	23	26	26	26	26	26
1	Rural	12	Semi-motorway	1	Free-flow							95		110			
1	Rural	12	Semi-motorway	2	Heavy							87		101			
1	Rural	12	Semi-motorway	3	Saturated							71		71			
1	Rural	12	Semi-motorway	4	Stop-&-go							23		26			
1	Rural	20	Trunk road	1	Free-flow				63	68	74	74	80	94	100		
1	Rural	20	Trunk road	2	Heavy				51	50	65	65	72	74	90		
1	Rural	20	Trunk road	3	Saturated				30	31	31	31	31	31	31		
1	Rural	20	Trunk road	4	Stop-&-go				23	23	23	23	23	26	26		
1	Rural	30	Distributor	1	Free-flow			49	53	68	74	80	94				
1	Rural	30	Distributor	2	Heavy			38	40	50	65	72	74				
1	Rural	30	Distributor	3	Saturated			24	28	31	31	31	31				
1	Rural	30	Distributor	4	Stop-&-go			13	19	19	19	23	26				
1	Rural	31	Distributor-sinuous	1	Free-flow			38	40	50	65	65	74				
1	Rural	31	Distributor-sinuous	2	Heavy			38	40	50	65	65	74				
1	Rural	31	Distributor-sinuous	3	Saturated			24	28	31	31	31	31				
1	Rural	31	Distributor-sinuous	4	Stop-&-go			13	19	19	19	23	26				
1	Rural	40	Local	1	Free-flow			40	53	64	74						
1	Rural	40	Local	2	Heavy			38	40	50	65						
1	Rural	40	Local	3	Saturated			20	28	31	31						
1	Rural	40	Local	4	Stop-&-go			13	19	19	19						
1	Rural	21	Local-sinuous	1	Free-flow			38	40	50	65						
1	Rural	21	Local-sinuous	2	Heavy			38	40	50	65						
1	Rural	21	Local-sinuous	3	Saturated			20	28	31	31						
1	Rural	21	Local-sinuous	4	Stop-&-go			13	19	19	19						
1	Rural	50	Access	1	Free-flow	20	33	37									
1	Rural	50	Access	2	Heavy	20	33	37									
1	Rural	50	Access	3	Saturated	13	14	26									
1	Rural	50	Access	4	Stop-&-go	11	12	13									
2	Urban	10	Motorway-national	1	Free-flow						74	76	94	100	118	118	
2	Urban	10	Motorway-national	2	Heavy						72	72	74	90	90	90	
2	Urban	10	Motorway-national	3	Saturated						31	31	31	31	31	31	
2	Urban	10	Motorway-national	4	Stop-&-go						23	23	26	26	26	26	
2	Urban	11	Motorway-city	1	Free-flow				63	64	74	76	94	100			
2	Urban	11	Motorway-city	2	Heavy				51	50	72	72	74	90			
2	Urban	11	Motorway-city	3	Saturated				30	31	31	31	31	31			
2	Urban	11	Motorway-city	4	Stop-&-go				23	23	23	23	26	26			
2	Urban	20	Trunk road - national	1	Free-flow					64	74	76	94	100			
2	Urban	20	Trunk road - national	2	Heavy					50	65	65	74	90			
2	Urban	20	Trunk road - national	3	Saturated					31	31	31	31	31			
2	Urban	20	Trunk road - national	4	Stop-&-go					23	23	23	26	26			
2	Urban	21	Trunk road - city	1	Free-flow			44	63	64	74	76					
2	Urban	21	Trunk road - city	2	Heavy			36	51	50	65	65					
2	Urban	21	Trunk road - city	3	Saturated			17	30	31	31	31					
2	Urban	21	Trunk road - city	4	Stop-&-go			13	23	23	23	23					
2	Urban	30	Distributor	1	Free-flow			45	53	64	74						
2	Urban	30	Distributor	2	Heavy			38	40	50	65						
2	Urban	30	Distributor	3	Saturated			24	28	31	31						
2	Urban	30	Distributor	4	Stop-&-go			13	19	19	19						
2	Urban	40	Local	1	Free-flow			40	53								
2	Urban	40	Local	2	Heavy			38	40								
2	Urban	40	Local	3	Saturated			20	28								
2	Urban	40	Local	4	Stop-&-go			13	19								
2	Urban	50	Access	1	Free-flow	20	33	37									
2	Urban	50	Access	2	Heavy	20	33	37									
2	Urban	50	Access	3	Saturated	13	14	26									
2	Urban	50	Access	4	Stop-&-go	11	12	13									

B2.6 Summary of traffic parameter studies

For several traffic-related parameters, the data and assumptions used for emission estimation appeared to be quite poor or even arbitrary. However, improvements could be made using existing published statistics. Such information was collected and analysed in order to derive plausible European or national figures. The principal objective of this work was to derive a representative set of default values for Europe. Specific studies and reports were also conducted in relation to the following: (i) vehicle load factors and the empty running rates, (ii) annual mileages, (iii) fuel characteristics, (iv) trip lengths, and (v) survival and scrappage rates.

B2.6.1 Load factors and empty running rates

Statistics on load factors and empty running rates were collected both for Europe and individual countries. An analysis of the statistics highlighted various difficulties (Adra *et al.*, 2004). It was recommended that load factors and empty running rates should be considered as functions of vehicle type and size, and their evolution with the time should also be taken into account. For goods transport, the following conclusions were drawn:

Load factor

(i) The difference between the load factor for loaded trips (excluding empty running) and the load factor for all trips (including empty running) is not always clear. More work is needed at the European level to provide clear definitions and harmonised, reliable data on load factors.

(ii) It is strongly recommended that the following definitions are adopted: (i) the empty running corresponds to the mileage driven without load, (ii) the average load factor is the average ratio between the actual load weight during non-empty running and the load capacity of the vehicle.

(iii) The load factor depends on the vehicle type and weight. For example, rigid heavy goods vehicles with a gross weight of between 3.5 and 7.5 tonnes had an average load factor of 42%, whilst a rigid heavy goods vehicle over 25 tonnes had an average load factor of 65%.

(iv) The average load factor in the EU ranges from 35% to 80%, and is gradually decreasing with time. This decrease can be due to the increase of the loading capacity per vehicle, and to reductions in the weight transported per trip (lower densities of modern high-quality goods). Corrections functions for time have been established for rigid and articulated vehicles. These enable the load factor to be determined for a given year n as a function of the load factor at n_0, using:

$$LF(n) = P*(n-n_0) + LF(n_0) \qquad \text{(Equation B2-2)}$$

where $LF(n_0)$ is the load factor at a year n_0.

This function was adapted to the vehicle types used in COST346.

Empty running rate

(i) The empty running rate is decreasing with time. Relationships to estimate the rate for a given year have also been derived from the available data.

(ii) The empty running rate also depends on the age of the vehicle.

(iii) The use of an empty running rate of 25% (as sometimes used) is close to the average values for Great Britain (26.5% in 2002) and in France (25.2% in 2001).

(iv) Where data are available, a distinction should be made between the two modes of working: 'hire' or 'reward' (22% and 35% respectively in France in 2001).

(v) The distinction between rigid vehicles and articulated vehicles should also be clear.

B2.6.2 Annual mileage

In order to take better account of annual mileage when estimating pollutant emissions, corrections for time and usage should be applied for the different vehicle weight categories (Adra and André, 2004c):

- French and British statistics show significant variation between rigid and articulated vehicles: usage factors are 0.6 to 1.4 in France and 0.7 to 1.8 in UK.
- The distinction between rigid vehicles and articulated vehicles should again be clear. A ratio of 1.4-1.8 could be used.
- Important variations are observed according to vehicle weight.
- A significant variation is observed as a function of the mode of working (public haulage or private use): public haulage generally leads to a more intensive use of the vehicle (usage factors are respectively 1.4 for public haulage and 0.5-0.7 for private use). If data are available, the distinction should be made.

- The annual mileage varies with time.
- Where data are available, a distinction between payload categories of vehicle should be made.

B2.6.3 Fuel characteristics

The European Commission has collected information on fuel quality since 2001. The information is summarised in annual reports. The Commission's fuel quality monitoring report provides a reliable data source, and the values it contains can be used by countries for their emission calculations. Important discrepancies can, however, be observed between countries. Where data are available, regional and seasonal specificities must be considered (Adra and André, 2004b).

B2.6.4 Trip length

The collection and analysis of data and statistics on trip length from different sources highlighted trends and the influence of various factors (Adra and André, 2004a). On the European level, although some countries collect information on trip characteristics and trip length, it seems that:

- No EU-wide data are yet available for passenger cars. Even fewer data are available for goods transport.
- There is no standard data set for all countries.
- There is no common definition of a 'trip'.

The following definition is recommended for adoption: a 'trip' is a one-way movement of a vehicle between the engine starting and the engine stopping. The 'trip length' is then the distance between the two points.

Passenger cars

On the European level, there is a lack of standard data sets for trip description. The EU-average trip length is 13 km and is increasing with time. The average value from vehicle instrumentation is 7 km. A number of important factors are evident:

(i) Factors relating to the driver (*e.g.* age, sex, professional and marital status, income).
(ii) Factors relating to the trip (*e.g.* trip purpose, trip type, type of use), to the vehicle (e.g. vehicle type).
(iii) Factors relating to the local context (*e.g.* residential area, city size, origin and destination, *etc*), and to the time (*e.g.* season, day of the week, time period).

The inclusion of such correction factors should improve emission estimates.

Goods transport

For goods transport there are few available data concerning the description of trip length. The existing information relates to the length of haul, the goods transported, and their flow (tonne-kilometres). The factors which can influence the length of haul are:

(i) The year. In Sweden the average duration of haul has increased by 20% from 1993 to 2001.
(ii) Vehicle type. Articulated vehicles carry goods three times further than rigid vehicles.
(iii) Vehicle size. The variation with vehicle size is more important for rigid vehicles, and is particularly significant for the vehicles with a weight of 17-25 tonnes.
(iv) Goods category. Data from Sweden and Great Britain show that the haulage distance varies greatly depending on the category of goods being carried.
(v) For local and regional approaches, it is necessary to define specific distributions for trip lengths, as these seem highly dependent on local characteristics.

B2.6.5 Survival and scrappage rates

An accurate description of the fleet composition and its evolution with the time is necessary for emission calculations. On the basis of vehicle registration data, the fleet evolution can be estimated using the number of vehicle scrapped each period (scrappage rate), or the proportion of vehicles surviving each period (survival rate). These rates are important, as they determine the longevity of vehicles within the fleet and influence the number of new vehicles entering the fleet each year, ultimately affecting emissions. A review of the available data on survival and scrappage rates from different sources was conducted by Adra and André (2004c), which underlined the following points:

(i) Survival rates or functions are the main methods used to determine the vehicle stock.

(ii) Methodological discrepancies exist between countries and institutions. In some European countries (*e.g.* Sweden), annual fleet composition data are available from the official statistics, and thus survival rates can be calculated for each year and each vehicle type. In the United States, different survival rates are given for different model years.

(iii) The survival rate is an important criterion in the calculation of pollutant emissions. Care should be taken in the choice and the use of survival rates, especially for countries which do not have their own data. National policies such as scrappage schemes should be taken into account.

(iv) In most cases, assumptions are made to derive the fleet composition at the level of detail required.

(v) There are differences between the definitions used in the different approaches (survival rate, lifetime function, scrappage rate, absolute and relative survival rates, *etc*).

(vi) Methods which take into account imported used cars can be important for some countries.

(vii) The method of determining future survival rates is not always reliable.

The following recommendations were made:

(i) For ARTEMIS, the same definition of 'survival probability' and 'lifetime function' must be used by all the partners.

(ii) Country-specific survival rates must be defined for the emission calculation.

(iii) The fleet composition module uses survival probabilities by segment for all years. This type of data may be not available in some countries, at least at the level of detail required. Therefore, assumptions must be made and default survival rates should be proposed in ARTEMIS.

B2.6.6 Speed

An accurate and detailed knowledge of actual driving speeds is fundamental for emission estimations and inventories. A review of the speed data available from different sources was conducted by Fantozzi *et al.* (2005b). The review highlighted the difficulties in obtaining reliable and detailed speed data. Various information is available through measurements, surveys and modelling exercises. However, the data are often limited to average speed values. Speed distributions and speed profiles (or speed x acceleration matrices) can be obtained from instrumented vehicles, but the data are often incompatible with the degree of detail that would be needed.

Furthermore, a data collection process was initiated in ARTEMIS and COST346 to obtain continuous speed data for detailed traffic situations, as required for the emission estimation approach at this level. Although speed data were obtained for hundreds of traffic situations, this stage of the emission estimation remained a weak point on account of missing data and poor representativeness.

B2.6.7 Traffic datasets in Central and Eastern European countries

A specific investigation of vehicles parameters in Central and Eastern European countries was also conducted (Pollak, 2000). This revealed large gaps and a number of inconsistencies in the data. The following issues were raised:

(i) Careful consideration should be given to new cars and imported used cars

(ii) Statistics which are common in Western Europe were often not available, including:
- the average annual mileage
- the average age of vehicles
- the number of buses and goods vehicles per size category
- the distinction between motorcycles and mopeds distinction

(iii) The total traffic activity (vehicle-km) and the passenger transport activity (passenger-km) are generally not available in most countries.

Further effort will be needed to collect available statistics in Central and Eastern European countries for emission modelling purposes. It may be possible to use default data based on the statistics from other countries.

B2.7 Conclusions

The road traffic characteristics required for the estimation of emissions constitute a considerable field of investigation, and have received poor coverage to date. The uncertainty in emission estimates remains strongly associated to the traffic-related parameters, which are themselves often highly uncertain.

The work conducted within ARTEMIS – although largely insufficient – has enabled significant progress in this area. The main achievements included the following:

(i) The design of traffic structures and the identification of parameters that have to be considered in the estimation of pollutant emissions from the road transport (vehicle fleet, definition of 'traffic situations').

(ii) The development of a complete modelling approach to estimate emissions on a local scale, and the collection of speed-related data for each of the defined traffic situations and vehicle categories.

(iii) Several studies have collated existing statistics relating to parameters such as the load factors, annual mileages, vehicle survival rates, speed, *etc*. Although not directly applicable within the ARTEMIS tool, these studies have clearly indicated gaps in the data and have identified the pertinent parameters. They should be used as a basis for constituting default datasets for the emission estimation tools.

(iv) A specific investigation in the Central and Eastern European countries revealed large gaps and a number of inconsistencies in the traffic data, but represented a useful starting point for further work.

Further work is recommended on the following topics:

(i) The provision of reliable and detailed speed data for different vehicle categories within the high number of traffic situations that have been defined.

(ii) The validation of emission estimation approaches at different scales, particularly in relation to the traffic data needed at these scales.

(iii) To derive default values for important parameters such as load factors or survival rates.

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B3 PASSENGER CARS

B3.1 Introduction

This Section of Part B describes the work conducted in ARTEMIS on exhaust emissions from passenger cars. The Section is a summary of the main technical reports on the subject (Joumard *et al*., 2006, 2007).

The work was conducted in three main Phases:

- Phase 1 - An assessment of the accuracy of emission measurements.
- Phase 2 - The improvement of the European database of measurements used for model development.
- Phase 3 - The development of new emission models.

Phases 2 and 3 also covered light commercial vehicles, although this aspect of the research is described in Part B4 of the Report.

B3.1.1 Accuracy of emission measurements

In the MEET project and the COST 319 Action, emission factors for regulated pollutants were developed using existing data in Europe (European Commission, 1999a, 1999b). However, one of the main conclusions was that there were large differences between the emission levels measured at different laboratories and within individual vehicle categories. In order to produce accurate emission factors for current and near-future vehicle technologies, a two-fold strategy was therefore adopted in ARTEMIS:

(i) *An investigation of the measurement differences between laboratories*

Methods of emission measurement have been partially standardised in legislation. Although many of the parameters influencing emission measurements are well known, their actual effects have not been well quantified. This is especially pertinent for the most modern cars, as their emissions can be very low but also very sensitive to changes in measurement conditions. This undermines the production of accurate emission factors. The ARTEMIS test programme was therefore designed according to the following requirements:

- Specific vehicle models had to be selected according to their contribution to the fleet population.
- Vehicles had to be tested over cycles which covered a wide range of real-world operational conditions.
- The effects of mileage and the deterioration of emission-control equipment had to be investigated in more detail.
- The systematic differences between laboratories had to be examined in detail.

(ii) *Investigating, understanding and modelling the emission differences between comparable vehicles*

In MEET, large differences were observed between the emission levels of cars which were compliant with the same emission standard, were of the same size, had more or less the same mileage, and were operated over similar driving cycles. Again, these differences were found to be much more pronounced for the most recent vehicles (Euro II at the time). A number of studies conducted prior to ARTEMIS indicated that the reasons for these differences included the following:

- Emission levels which were close to the detection limits of analysers.
- Different engine management and emission-control concepts.
- Different responses to driving cycles (*e.g.* speed, acceleration, engine load, idle time).
- Differences in vehicle mileage, age and level of maintenance.
- Differences in other parameters, such as the test conditions, the laboratory, *etc*.

On the basis of the above, the main objectives of the ARTEMIS work were the following:

(i) *To study the sensitivity of pollutant emissions to key parameters*

These parameters were divided into four main categories:

- Driving behaviour parameters, such as the driving cycle and the gear-shift strategy.
- Vehicle-related parameters, such as the engine management and emission control concept, the emission stability, mileage, age, maintenance level, and fuel properties.
- Vehicle sampling parameters, such as the way in which test vehicles are chosen by a laboratory, and the number of vehicles tested in each category.
- Laboratory-related parameters, such as the ambient test conditions, the dynamometer settings and the analytical equipment used.

Some of these issues were addressed via reviews of the literature, or by the processing of existing emissions data. For others, new laboratory measurements were required.

(ii) *To develop methods which allow the harmonisation of European emission measurements*

This involved establishing 'standard' conditions in order to obtain comparable data, and building methods to extend the data to any European condition. The approach was designed to improve the accuracy of European emission models, and to greatly enlarge the range of application for such models. A further objective was the design of a best practice guide for measuring emissions.

This work is summarised in Section B3.2.

B3.1.2 Improvement of emission factor database

The vast majority of the emission data for European road vehicles has been obtained for the regulated pollutants and CO_2, and for passenger cars. In order to respond to new concerns relating to air pollution, ARTEMIS required a much better understanding of types of emission process and pollutant which had not previously been studied in detail (Joumard *et al.*, 2007). Although further extensive measurements of regulated pollutant emissions from passenger cars under standard test conditions were conducted in ARTEMIS, significant resources were also directed towards addressing several other important aspects for which very few data existed, in order to improve the overall database of emission factors and the associated modelling tools. These aspects - which are addressed in Section B3.3 unless stated otherwise stated - were:

(i) Road gradient and vehicle load.

(ii) Unregulated pollutants. The speciation of VOCs is useful for modelling photochemical pollution. Greenhouse gases, PAHs, and particulate size are important in the assessment of climate change and health effects.

(iii) Cold-start emissions. These are covered in Part B7 for passenger cars, and in the appropriate Parts of the Report for other vehicle types.

(iv) Auxiliary systems. The effects on emissions of the additional electrical load due to auxiliary systems - such as air conditioning, headlights and radios are not well known.

(v) Light commercial vehicles. These are covered in Part B4.

B3.1.3 Development of new models

The ARTEMIS emission model for road transport contains three principal sub-models for hot emissions, cold-start emissions and evaporative emissions[10]. The models for cold-start emissions and evaporative emissions are discussed in Parts B7 and B8. The modelling of hot emissions in ARTEMIS is described in this Part of the Report.

ARTEMIS followed on from, and was designed to replace, the two main inventory models in use in Europe - MEET/COPERT III, and the Handbook of Emission Factors (HBEFA) which is used in Austria, Germany and Switzerland. The main difference between the MEET/COPERT and HBEFA is the approach to driving kinematics. In MEET/COPERT this is addressed through the use of trip average speed alone, but in HBEFA discrete traffic situations are used.

In the ARTEMIS project, the most recent and comprehensive data on emissions were used to further develop these approaches. In fact, four different types of emission model were developed in ARTEMIS:

- Instantaneous emission models.
- A kinematic regression model.
- A traffic situation model.
- Average speed models.

The development of these models is discussed in Section B3.4.

B3.1.4 ARTEMIS light vehicle emission measurement (LVEM) database

The database used to derive the ARTEMIS light vehicle emission models included existing European emission data, either already collected within MEET and COPERT (or collected at a later date), and the results of the vehicle tests carried out specifically within ARTEMIS by the different partners. All the available data were combined in the ARTEMIS LVEM database. This database is presented in section B3.5.

B3.2 Accuracy of emission measurements

B3.2.1 Overview of experimental work

The ARTEMIS measurement programme was designed in response to the main objectives of the project - *i.e.* the determination of reliable emission factors for European passenger cars, and the analysis of the measurement conditions potentially influencing these emission factors. A reference set of real-world driving cycles was developed for use by all the

[10] For PM, non-exhaust sources such as tyre wear and brake wear are also important.

project partners in order to improve the representativeness of the emission tests and the comparability of the measurements made in different laboratories. The development of this set of cycles is summarised in Section B3.2.2.

Emission tests were conducted at nine participating laboratories using a chassis dynamometer. The fuels used during the tests were obtained from local retail outlets. The regulated pollutants (CO, HC, NO_x and PM) and CO_2 were collected using a constant volume sampler (CVS). Pollutants were collected as bag or filter samples, and were also measured continuously. Standard analytical techniques were used (NDIR[11] for CO and CO_2, chemiluminescence for NO_x, flame ionisation detection for HC, and filter weighing for PM). Fuel consumption was calculated using the carbon balance method.

The actual parameters studied in ARTEMIS are summarised in **Table B3-1**. A separate programme was designed for each parameter except the vehicle sampling method, for which information was obtained directly from the laboratories. The vehicle sample sizes for each task are listed by fuel and emission standard in **Table B3-2**. It was also considered necessary to compare the laboratories by performing a 'round-robin' test programme on a single reference vehicle.

A total of 183 vehicles were tested during the ARTEMIS project, and data from 81 previously tested vehicles were also used. The detailed characteristics of all the test vehicles are given by Joumard *et al*. (2007).

In total, 2,753 tests were carried out, of which:

- 537 tests examined the influence of driving behaviour.
- 1,334 tests examined the influence of vehicle parameters.
- 672 tests examined the influence of laboratory-related parameters.
- 210 tests were conducted for the round-robin exercise.

In addition, the results from more than 900 existing tests (pre-ARTEMIS) were processed and analysed.

The studies of the individual parameters, including the method used and the results obtained, are briefly summarised in Sections B3.2.3 to B3.2.6. The tests are described in detail in dedicated reports compiled for each parameter studied, and references to these reports can be found in the relevant Sections. The methodology for the round-robin test programme is summarised in Section B3.2.7.

Table B3-1: Parameters studied, with an indication of the approach used.

Type of parameter	Parameter	Literatur e review	Reprocessing of old data	New tests
Driving behaviour	Driving cycle	✓	✓	✓
	Gear-shift behaviour			✓
	Influence of the driver		✓	
Vehicle-related	Technological characteristics	✓		✓
	Emission stability			✓
	Emission degradation	✓		✓
	Fuel properties	✓		✓
	Cooling fan operation			✓
	Vehicle preconditioning			✓
Vehicle sampling	Method of vehicle sampling	✓		
	Vehicle sample size	✓	✓	
Laboratory-related	Ambient temperature			✓
	Ambient humidity			✓
	Dynamometer settings			✓
	Dilution ratio			✓
	Sample line temperature			✓
	PM filter preconditioning			✓
	Response time	✓		✓
	Dilution air conditions			✓
Round-robin test				✓

[11] NDIR = non-dispersive infra red spectrospcopy.

Table B3-2: Vehicle samples per parameter in terms of fuel and emission standard. Vehicles in brackets were tested as part of former research projects, or represent a sub-sample taken for more detailed analysis.

	Parameter	Total.	Petrol						Diesel					
			Pre-Euro I	Euro I	Euro II	Euro III	Euro IV	Total	Pre-Euro I	Euro I	Euro II	Euro III	Euro IV	Total
Driving	Driving cycle	33		3	7	6 *(4)*		16	2	3 *(2)*	10	2 *(1)*		17
	Gear-shift behaviour	15		3	3	2		8		2	4	1		7
	Influence of the driver	*1*		*1*				*1*						*0*
Vehicle	Tech. characteristics	43			3	23	6 *(3)*	32			2	9 *(5)*		11
	Emission stability	12		1	3	6		10				2		2
	Emission degradation	2				2		2						0
	Fuel properties	2				1		1				1		1
	Cooling fan operation	6			4			4			1	1		2
	Vehicle	5			2	1		3			2			2
	Vehicle sample size	*80*	*34*	*18*	*3*			*55*	*11*	*9*	*5*			*25*
Laboratory	Ambient temperature	31	6		7	7	2	22			8	1		9
	Ambient humidity	11			4	5		9			2			2
	Dynamometer settings	5			3			3			2			2
	Dilution ratio	8			2	1		3			3	2		5
	Sample line	1						0			1			1
	PM filter	1						0				1		1
	Response time	5	1	1	1			3			1	1		2
	Dilution air conditions	2			1		1	2						0
Round-robin tests		1				1		1						0
Total		183	7	8	40	55	9	119	2	5	37	20	0	64

a including one CNG vehicle
b including two CNG vehicles

B3.2.2 The common ARTEMIS driving cycle

In order to improve the representativeness of the ARTEMIS emission tests, and the comparability of the measurements made in different laboratories, a reference set of real-world driving cycles was developed for use by all the project partners. The development of these driving cycles was conducted in four stages: (i) the observation of vehicle usage and operating conditions, (ii) the analysis of driving conditions, (iii) the analysis of vehicle trips and (iv) the development of representative driving cycles. The principles applied are described by André (2004), and are briefly summarised below.

The work was based upon a large database of European driving patterns derived from a series of on-board monitoring experiments on private cars in France, Germany, Greece and the UK (André, 1997). In all, 77 vehicles were monitored over 10,300 trips. These trips covered a total distance of 88,000 km, and had a total duration of 2,200 hours. Vehicle usage and operating conditions, such as speed, acceleration, engine operation, trip information, gearbox use, and engine thermal condition, were recorded in detail. Complementary data were used to validate the results, including driving patterns recorded in Naples by Rapone *et al.* (1995) and in Switzerland by Keller *et al.* (1995). Different types of driving condition were defined via the analysis of driving patterns according to their idling duration and a two-dimensional matrix of instantaneous speed and acceleration. Three main real-world driving cycles - ‘urban’, ‘rural’, and ‘motorway’ - were then constructed to represent driving according to the respective area/road types (André, 2004). Two versions of the motorway cycle were produced, one with a maximum speed of 150 km/h and one with a maximum speed of 130 km/h. The latter was developed for use on emission testing facilities which are not capable of operating at the higher speed. Some of the cycles included a ‘pre-’ or ‘post-’ phase to allow trip start and end conditions to be defined. Different gear-shift strategies were also reviewed, with a simplified approach being adopted for ARTEMIS (André, 2004). The main ARTEMIS cycles, including a number of sub-cycles, are shown in **Figure B3-1**. The complete set of cycles is referred to as the ‘ARTEMIS driving cycles’.

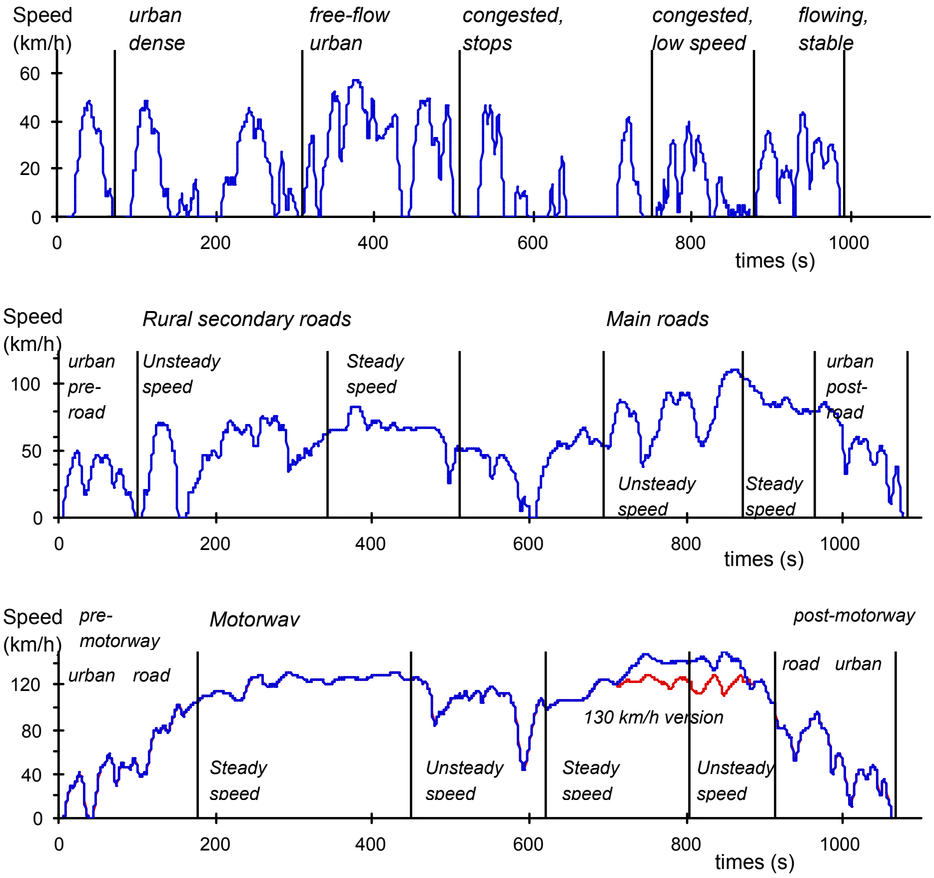

Figure B3-1: The ARTEMIS urban, rural and motorway driving cycles, including sub-cycles and starting conditions (André, 2004).

As the ARTEMIS driving cycles were constructed using representative real-world driving patterns, it is possible to estimate emissions for a wide range of traffic situations by combining and weighting the cycles and sub-cycles. A statistical approach of this kind is described by André (2004). The development of the ARTEMIS cycles was widely discussed and approved, and the cycles are now used extensively in European research projects and national programmes for the measurement and modelling of pollutant emissions.

B3.2.3 Driving behaviour parameters

Driving cycle

The aims of this part of the work were to review and compare existing passenger car driving cycles in relation to their kinematics, their representativeness and their method of development, and to determine the sensitivity of emission measurements to driving cycle characteristics. The specific objectives were as follows:

- To identify kinematic parameters which would enable detailed emission modelling to be undertaken.
- To harmonise and analyse the complex and varied dataset of passenger car emission factors collected within ARTEMIS.
- To establish an emission modelling approach which could be used at the local (or 'street') level.

The work was conducted in three stages:

Stage 1: Analysis of the ARTEMIS driving cycle database for passenger cars, and selection of contrasting driving cycles.
Stage 2: Analysis of emission data in relation to driving conditions.
Stage 3: Harmonisation of the full ARTEMIS emission factor database for passenger cars.

<u>Stage 1: Selection of contrasting driving cycles for passenger cars</u>

The first stage of the analysis involved the collection and review of 213 different real-world passenger car driving cycles or sub-cycles (André *et al.*, 2006), and the selection of contrasting cycles for the measurement and analysis of emissions in relation to driving conditions. These cycles were characterised in terms of their kinematic content - principally via a two-dimensional distribution of instantaneous speed and acceleration. Due to the wide variation in driving cycle dynamics a classification of the cycles was conducted, which enabled the selection of 14 cycles and 40 contrasting sub-cycles. This set of cycles provided coverage of many real-world driving conditions, as shown in **Figure B3-2**. The 14 driving cycles included the main ARTEMIS cycles, cycles used in HBEFA, and cycles from Napoli. Their detailed characteristics are given by Joumard *et al*. (2006a). The cycles were used to test a sample of nine passenger cars.

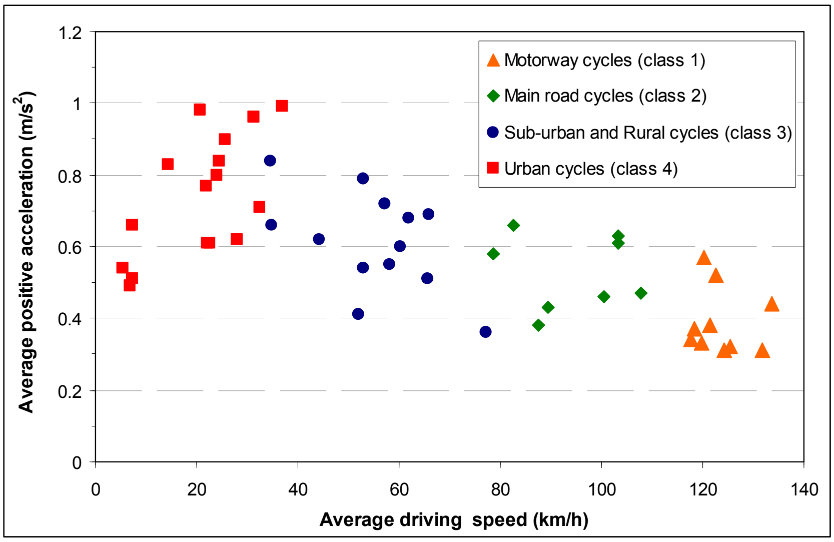

Figure B3-2: Final selection of the cycles and corresponding sub-cycles and their coverage as regards running speed and acceleration.

A second set of vehicle-specific driving cycles was also used to assess the effects of driving conditions. These cycles were derived using the same database and principles as the ARTEMIS cycles, but considered two classes of vehicle according to power:mass ratio (low-powered cars with 61 W/kg or less, and high-powered cars with more than 61 W/kg) and urban, rural and motorway driving conditions (André, 2004, study funded by ADEME). Although they were similar in structure, these cycles offered a significant contrast in terms of dynamics. A sample of 30 French cars was used in the tests.

Stage 2: Analysis of emission data as in relation to driving conditions.

The emission factors in the two datasets described above were analysed with respect to factors such as fuel type, driving type and cycle, dataset, vehicle category, *etc*., as well as a large range of kinematic parameters such as speed, acceleration, stop frequency, time distributions of speed and acceleration, *etc*. Analysis of variance was used to identify the level at which analyses could be conducted, and then to determine the relative effects of different factors and parameters. The findings of this work are summarised in **Table B3-3**.

For the whole dataset, the fuel type (petrol, diesel), the emission standard, the main driving type (urban, rural, motorway/main road), the driving cycle, and the vehicle itself were identified as the most important factors. However, the variation associated with the main driving type or cycle was greater than the variation associated with the other factors. This highlights the importance of the driving cycle on emissions. For diesel cars, it appeared that the driving type, the driving cycle and the vehicle itself were the most important factors determining emissions, whereas for petrol cars the vehicle and the emission standard were the most important factors. A clear contrast was observed between the emission behaviour of diesel vehicles, which were rather sensitive to speed and stop parameters, and petrol cars, which were rather sensitive to accelerations. The analysis of Euro II and Euro III vehicles demonstrated that urban congested driving with many stops resulted in high CO_2 emissions from petrol and diesel cars, and high NO_x emissions from diesel cars. During motorway driving, stable high speeds (*e.g.* ARTEMIS motorway, 150 km/h, 'steady speed' – see **Figure B3-1**) generated high CO_2 emissions, whilst unstable high speeds (*e.g.* ARTEMIS motorway, 150 km/h, 'unsteady speed') led to higher NO_x emissions from diesel cars and higher CO emissions from petrol cars.

The measurements conducted using both the vehicle-specific cycles and the ARTEMIS cycles demonstrated that the use of a common test procedure (as in ARTEMIS) instead of cycles adapted to vehicle power could lead to very different emission estimates, particularly for the most recent vehicle categories. For Euro II and III vehicles, CO emissions from petrol cars were under-estimated by 15-20%. For diesel cars, emissions of HC and PM were under-estimated, and CO emissions were over-estimated by 20%. The use of a common set of cycles led to a significant over-estimation of urban emissions (6-10% for NO_x and CO_2, 15-20% for CO and HC), whilst rural and motorway emissions were slightly under-estimated. Finally, it was found that for low-powered cars, CO_2 emissions and fuel consumption were higher (by 11 %) when measured using a common set of cycles than when measured using the vehicle-specific cycles. The common cycles also led to an under-estimation of CO and HC emissions for small cars (by 4-13%) and a slight over-estimation of HC and NO_x (10%) from the most powerful cars. Consequently, in the future consideration should be given to the use of vehicle-specific driving cycles to measure pollutant emissions more accurately.

Table B3-3: Effects of driving type on emissions from petrol and diesel cars.

Vehicle type	Driving type	Observations
Diesel	Urban	Emissions of all pollutants increase with stop frequency and relative stop duration.
		Emissions of all pollutants except CO decrease as speed increases. CO emissions are sensitive to high speeds (60-100 km/h).
		NO_x and CO_2 emissions are sensitive to the frequency and strength of accelerations.
	Rural	Emissions of all pollutants increase with stop frequency and relative stop duration
		Emissions of all pollutants decrease as speed increases, and are sensitive to low speeds (20-40 km/h or less) and acceleration. CO emissions appear to be rather sensitive to the maximum acceleration or deceleration.
	Motorway/ main road	NO_x and CO_2 emissions are sensitive to high speeds (120-140 km/h) and to the variation in speed (standard deviation of speed), but emissions decrease at intermediate speeds (60-100 km/h)
		CO emissions increase with the occurrence of intermediate or low speeds, stops and accelerations, but are low at high speeds.
Petrol	Urban	Emissions of all pollutants are sensitive to acceleration (mean, frequency, strength, time spent at high accelerations).
		CO and HC emissions are sensitive to high speeds (60-100 km/h) and strong accelerations.
		Emissions of CO_2 and HC increase with the number of stops. CO_2 decreases as the speed increases.
	Rural	Emissions of all pollutants are sensitive to acceleration (mean, frequency, strength, time spent at high accelerations).
		Emissions of CO_2, HC and NO_x increase with the stops duration and frequency.
		Emissions of CO_2 and NO_x decrease as the speed increases.
	Motorway/ main road	Emissions of all pollutants are sensitive to accelerations at high speeds. CO_2 and CO are high at high speeds (120-140 km/h and above) but low at intermediate speeds (60-100 km/h).

The full ARTEMIS emission factor database was also investigated using a hierarchical model to explain the total emission per driving cycle as a function of cycle characteristics. This model combined two individual partial least square regression sub-models. The first sub-model was based on dynamics-related parameters (speed, square and cubic speed, idling and total running times, average of the speed-acceleration product (positive), plus the inverse of the cycle distance). The second sub-model considered the two-dimensional distribution of the instantaneous speed and acceleration. Three diesel car classes (Euro I, II, III) and seven petrol car classes (Euro I, Euro II 1.1-1.4 l, Euro II > 1.4 l, Euro III 1.1-1.4 l, Euro III 1.4-2.0 l, Euro III > 2.0 l, Euro IV) were investigated. The results demonstrated once again that the driving cycle is an important factor affecting emissions, and that for petrol cars engine size has a significant effect on CO_2. For the sub-models the best fit between the observed and predicted emissions was usually obtained using the model based on the distribution of the instantaneous speed and acceleration. The average speed model was unable to predict the trends in emissions, and led to an over-prediction of emissions at high speeds.

Stage 3: Harmonisation of the full ARTEMIS emission factor database for passenger cars

The ARTEMIS database included tests from more than 20 European laboratories, conducted between 1980 and 2004 (André, 2005). It included 2,800 cars in most of the European legislative categories, 800 different cycles or sub-cycles, and 27,000 emission tests. From this database 20,000 emission tests were analysed (André *et al*., 2006b). The main purpose of this work was to standardise the database in relation to the driving cycle, prior to the generation of the final ARTEMIS emissions factors, and to develop a suitable modelling approach for use at the street level.

The significant influence of the driving conditions on emissions implied the need to apply a driving cycle correction to the emission factors in the ARTEMIS database prior to modelling. An approach based on kinematic similarity was developed. The approach consisted of three main steps:

(i) The grouping of cycles by kinematic content through the construction of a classification scheme.

(ii) The selection of appropriate cycles to represent each group.

(iii) The determination of corrections to develop reference emission factors.

More than 800 cycles and sub-cycles were included in the ARTEMIS database (Joumard *et al.*, 2006a). The most significant driving cycles in the database - the 98 cycles or sub-cycles for which there were significant numbers of emission test results - were used to develop the cycle classification scheme. The other cycles were not used in the construction of the scheme, but were classified according to it. The classification was based upon the two-dimensional distribution of instantaneous speed and acceleration. This procedure maximised both the homogeneity within cycle classes and the contrast between classes. The resulting 15 classes were termed 'Reference Test Patterns' (RTPs,). For each RTP, one of several 'Reference Test Cycles' (RTCs) were selected (**Figure B3-3**). Thirteen of the RTCs were combinations of the ARTEMIS cycles and sub-cycles. The two others represented congested driving and stable motorway driving (**Table B3-4**).

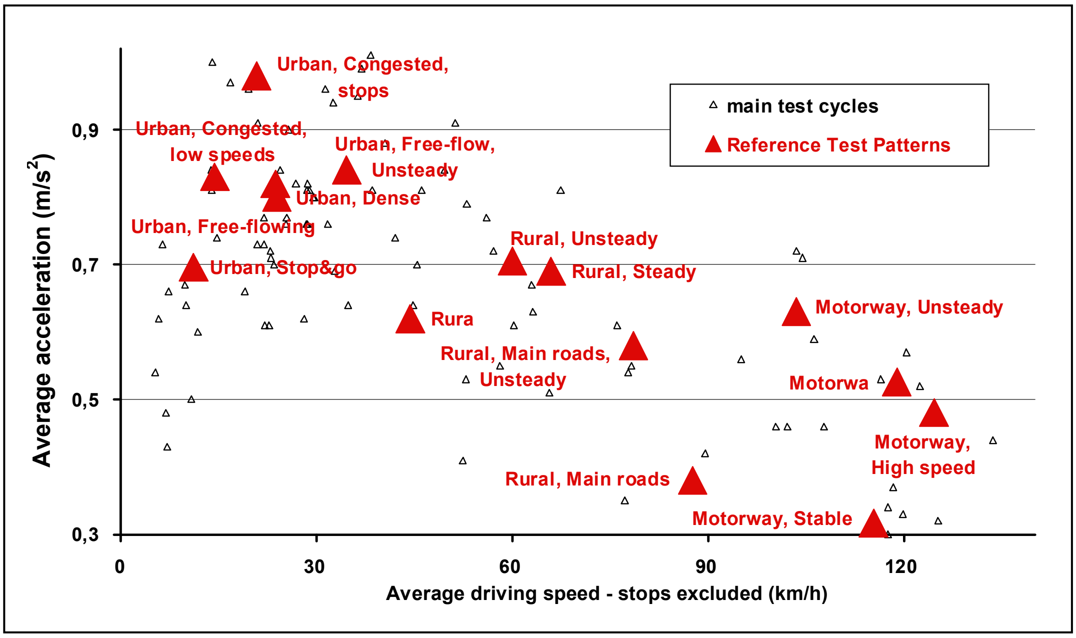

Figure B3-3: Map of the main RTPs.

Table B3-4: Classification of the RTPs and RTCs.

Reference Test Patterns (RTP)			Reference Test Cycles (RTC)	Average speed (km/h)	Average positive accel. (m s^{-2})	Stop duration (%)	Stop/km
7	Urban	Stop&go	OSCAR.H1, OSCAR.H2, OSCAR.H3, TRL-WSL CongestedTraffic	7	0.70	35	16.3
3	Urban	Congested, stops	ARTEMIS.urban_3	9	0.98	58	10.2
2	Urban	Congested, low speeds	ARTEMIS.urban_4	12	0.83	19	16.7
1	Urban	Dense	ARTEMIS.urban, ARTEMIS.urban_1	17	0.82	29	5.2
4	Urban	Free-flowing	ARTEMIS.urban_5	22	0.80	10	4.3
5	Urban	Free-flow, unsteady	ARTEMIS.urban_2	32	0.84	9	2.3
6	Rural		ARTEMIS.rural_3	43	0.62	3	0.5
11	Rural	Unsteady	ARTEMIS.rural, ARTEMIS.rural_1	58	0.71	3	0.3
9	Rural	Steady	ARTEMIS.rural_2	66	0.69	0	0.0
10	Rural	Main roads, unsteady	ARTEMIS.rural_4	79	0.58	0	0.0
8	Rural	Main roads	ARTEMIS.rural_5	88	0.38	0	0.0
14	Motorway	Unsteady	ARTEMIS.motorway_150_2	104	0.63	0	0.0
15	Motorway	Stable	EMPA.BAB modemHyzem.motorway TRL.MotorwayM113	115	0.32	0	0.0
13	Motorway		ARTEMIS.motorway_130 ARTEMIS.motorway_150_1	119	0.53	0	0.0
12	Motorway	High speed	ARTEMIS.motorway_150 ARTEMIS.motorway_150_3 ARTEMIS.motorway_150_4	125	0.48	0	0.0

An emission factor was allocated to each vehicle category, pollutant and RTP. The determination of emission factors was described by Joumard *et al.* (2007), and is also explained more fully in Section B3.4.3. RTPs can be combined in order to compute emissions for any traffic situation. According to Joumard *et al.* (2006), the process of classifying driving cycles and computing emissions per reference pattern are important aspects of a robust modelling approach, and should be used as the basis for defining emission functions in relation to speed and cycle dynamics.

The mapping of driving cycles in this way provided a good representation of driving conditions in relation not only to average speed, but also to acceleration (*i.e.* the dynamic of the traffic conditions). Indeed, two classes of driving could be clearly identified for certain pollutants (NO_x and CO_2) and vehicle categories: 'stable' driving with low acceleration and stop frequency, and 'unstable' driving.. The influence of this dynamic dimension is shown for NO_x in **Figure B3-4**.

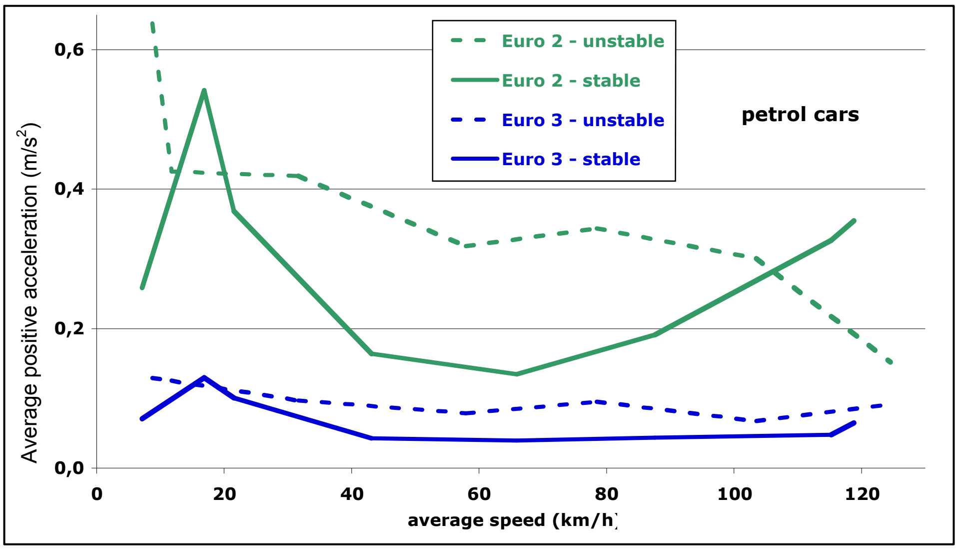

Figure B3-4: Dynamic influence on NO_x emissions for petrol cars under stable and unstable driving conditions.

Gear-shift behaviour

The effects of five different gear-shift strategies on emissions were evaluated in ARTEMIS, and these strategies are briefly described in **Table B3-5**.

Table B3-5: Description of the gear-shift strategies tested (André *et al.*, 2003).

Strategy	Description
'Cycle'	The gear-shift pattern is included in the design of the corresponding driving cycle (*e.g.* ARTEMIS).
'RPM'	The gear-shift criteria are defined in terms of given engine speeds.
'NEDC'	The gear-shift criteria are defined in terms of given vehicle speeds, as in the NEDC driving cycle.
'Record'	The gear-shift pattern is recorded on the road during data collection.
'Free'	The gear shifts are decided by the driver in the laboratory.

CO_2 was found to be the pollutant which was the most sensitive to the gear-shift strategy, with a systematic emission variation between strategies of between 2% and 15%. CO and HC showed significant differences between some strategies, but NO_x emissions were not influenced. It was therefore considered possible to classify gear-shift strategies only according to their CO_2 emissions. For the ARTEMIS driving cycles the most polluting strategy was the fixed engine speed (RPM) one, whatever the situation, and the least polluting strategy appeared to be the fixed speed (NEDC) one.

Influence of the driver

During an emission test the driver attempts to reproduce a pre-defined vehicle speed and gear-shift pattern, but the reproduction is never perfect. The objective of this part of the work was to identify the influence of the driver on the accuracy of the emission factors, and to propose guidelines which minimised the associated errors. A total of fifteen driving cycles were studied using a robot driver (Horiba ADS-1100) and four different human drivers. In order to compare the accuracy of the driving and the emissions obtained using the human drivers and the robot, four kinematic parameters were selected based on the difference between the reference speed and the actual speed (the 'speed error'): the mean standard deviation of the speed error, the mean absolute speed error, the auto-correlation of the speed error, and the regression coefficient between the actual and reference speeds (Devaux and Weilenmann, 2002).

The robot showed a slightly better repeatability than the human drivers, but the difference was not significant. Some driving cycles were too 'aggressive' for the robot, which affected the repeatability. Except for CO_2, no significant differences were found between emissions during robot-driven or human-driven tests. The CO_2 emissions of the human drivers were, on average, 4% higher than for the robot. It was suggested that motions of the accelerator pedal with frequencies above 0.5 Hz - undetectable in the 1 Hz data set - may have been responsible. From these results, it was also concluded that the initial goal of separating the variance of the emissions caused by the driver from the variance of the car, test bench and analysers could not be achieved (Devaux and Weilenmann, 2002).

An assessment was also made of the various tolerance ranges and fail criteria applied by each participating laboratory to the reference driving cycle. The criteria for failure should be meaningful and achievable in practice for most tests. However, the tolerance ranges should not be too wide in order to avoid unnecessary emission variation. It was concluded that, in general, it is possible for a trained driver to follow a real-world cycle with tolerance of ± 2 km/h and ± 1 second, such that the tolerance limits are violated for less than 1% of the test duration. These tolerance ranges were recommended for wider use. A tolerance range of ± 1 km/h and ± 1 second, on the other hand, leads to violation percentages of up to 50%. Higher violation percentages can arise under a number of conditions, such as when the car has insufficient power to follow the cycle, when wheel slip occurs, or when the car has a 'difficult' gearbox, resulting in slow gear changes.

B3.2.4 Vehicle-related parameters

Technological characteristics

A total of 43 cars were tested at different laboratories over the NEDC and the three main ARTEMIS cycles in an attempt to identify potential variations in the response of different emission control technologies to cycles with different dynamics, engine speed levels and power demand. However, a basic statistical analysis showed that only the type approval level (Euro II, III or IV) and the engine/fuel type (petrol or diesel) had a significant influence on emission levels, and these parameters are already used for vehicle classification in emission models (Samaras *et al.*, 2005a). No correlations between emission behaviour and specific emission-control technology were observed within the same type approval category. It is therefore unlikely that the introduction of detailed technological characteristics will improve the accuracy of emission databases for cars up to Euro IV.

Emission stability

The short-term stability of emission measurements was examined at each laboratory. After a preconditioning over the NEDC, the ARTEMIS urban cycle was driven five times. Each ARTEMIS cycle was preceded by a 20-minute break, so that the bag samples could be analysed and the dynamometer prepared for the next test. The second part of the test involved a similar sequence, but was performed using the ARTEMIS rural cycle. A total of 12 vehicles were tested, and the short-term emission stability was assessed using the standard deviation and relative standard deviation of the measurements. The measurement uncertainty could therefore be divided into the uncertainty due to between-vehicle differences (sample standard deviation) and that due to a spread in the results for one vehicle (relative standard deviation) (Cornelis *et al*., 2005).

The results showed that the different standard deviations varied considerably according to the pollutant and the vehicle class. The relative standard deviation was lowest for CO_2 (variation of 1% over the five repetitions). The relative standard deviations for HC and CO were high for most cars (up to 71%), but the absolute standard deviation was small. NO_x emissions from diesel cars proved to be highly repeatable. The relative standard deviations for CO, HC and NO_x were similar for Euro II and Euro III petrol cars. The sample standard deviation was always much higher than the relative standard deviation. This indicated that the differences between the test results of several vehicles are larger than the differences one might expect when testing the same vehicle several times. The results suggest that, for the derivation of emission factors, using a large sample of vehicles and a small number of repetitions for each tests cycle is preferable to using a small vehicle sample with a high number of test repetitions (Cornelis *et al*., 2005).

Emission degradation

The effects of vehicle age, mileage and level of maintenance over long periods were initially studied via a review of the literature and through the analysis of existing data. Two petrol vehicles were then subjected to a series of measurements. For both vehicles, the measurements were scheduled at mileage intervals of 20,000 km, and were performed both before and after maintenance. The test protocol involved a cold-start NEDC, followed by a EUDC. After the analysis of the bag samples, two repetitions of the EUDC were executed in order to achieve engine warm-up, and the three ARTEMIS cycles were then performed (Geivanidis and Samaras, 2004). No effect of maintenance was observed on the level of emissions, either as a consistent before-after maintenance improvement or as a function of mileage.

The correction factor approach to take into account the degradation of emissions with mileage was retained from the

COPERT III model (Ntziachristos and Samaras, 2000a), and is given by the equation:

$$MC_{C,i} = a_M \times M_{mean} + b_M \qquad \text{(Equation B3-1)}$$

where: $MC_{C,i}$ = the mileage correction for a given mileage, pollutant i and a specific cycle

a_M = the degradation of the emission performance per kilometre

M_{mean} = the mean fleet mileage of vehicles for which correction is applied

b_M = the emission level of a fleet of brand new vehicles

The value of b_M is always less than 1 because the correction factors are determined using vehicle fleets with mileages ranging from 16,000 to 50,000 km. Therefore, brand new vehicles are expected to emit less than the sample average. It was assumed that emissions do not further degrade above 120,000 km for Euro I and II vehicles, and above 160,000 km for Euro III and IV vehicles. The effect of average speed on emission degradation was taken into account by combining the observed degradation lines over the two driving modes (urban and rural). It was assumed that for speeds outside the region defined by the average speeds of urban driving (19 km/h) and rural driving (63 km/h), the degradation was independent of speed. Linear interpolation between the two values provided the emission degradation in the intermediate speed region.

For Euro I and Euro II vehicles, the data from MEET could be used, as most of the ARTEMIS data for these vehicles originated from MEET. In order to estimate the degradation of Euro III and Euro IV vehicles, the ARTEMIS data were used. Due to relatively small sample sizes, it was assumed that both Euro III and IV vehicles would have the same degradation behaviour. Mileage effects were only examined for CO, HC and NO_x, as CO_2 emissions are unaffected (Samaras and Ntziachristos, 1998; Ntziachristos and Samaras, 2000b, 2001). The analysis was performed for two types of driving - urban and rural. The emissions of all vehicles were plotted against their mileage for two engine capacity ranges (<1.4 l, and >1.4 l,), and linear regression lines were fitted to the data. The conclusions of the work were as follows:

- For CO during urban driving, a degradation was observed for each driving mode.
- For CO during rural driving, a degradation was observed for vehicles <1.4 l, while no degradation was observed for vehicles with engine capacities >1.4 l.
- For HC a considerable degradation was observed for vehicles <1.4 l in urban driving mode.
- For NO_x a considerable degradation was observed only for vehicles >1.4 l in urban driving mode.

Appropriate degradation functions are presented later in this Section. On average, the emissions of CO, HC and NO_x are multiplied by a factor of 3.6 between 0 km and 100,000 km for Euro I and II cars, and increase by 18% for Euro III and IV cars. For Euro I and II vehicles, NO_x (factor = 5.3) is more strongly influenced by mileage than CO and HC (factors = 2.9 and 2.7). However, NO_x emissions from Euro III and IV cars are not affected by mileage.

Fuel properties

The Auto/Oil and EPEFE programmes (hereafter referred to as EPEFE) provided equations to determine average exhaust emissions of regulated pollutants from petrol and diesel cars driven over the NEDC, according to fuel properties such as density, aromatic content, olefin content, sulphur content and cetane number (ACEA and EUROPIA, 1996). In ARTEMIS, these equations were used to predict which fuels would result in the minimum, maximum and average emission levels. Each participating laboratory sampled local unleaded petrol and diesel fuels, and these were subjected to compositional analysis. Based on the compositional data and the EPEFE equations, it was inferred that NO_x was the pollutant most strongly influenced by petrol fuel quality, and so this pollutant was used as the criterion for selecting petrol test fuels. PM was used to select diesel fuels. Three petrol fuels (from Austria, France and Greece) and three diesel fuels (from Finland, Italy and France) were selected. In addition, two Euro IV fuels were tested - one petrol and one diesel. Each fuel was tested with one vehicle, according to the following protocol: (i) a lubricant change to avoid carry-over effects, (ii) a preconditioning phase: a cold EUDC (followed by a EUDC for diesel fuel), (iii) a cold-start NEDC, (iv) a cold-start ARTEMIS urban cycle and (v) the three hot-start ARTEMIS cycles. All the tests were performed twice. When replacing fuels the car was also driven for a distance of between 150 and 200 km to remove any carry-over effect from the previous fuel (Renault and Altran, 2002).

For the petrol fuels, the highest CO emissions were obtained using the Austrian fuel over the cold-start ARTEMIS urban cycle. The aromatic content of this fuel was the highest of those tested. In such cases, the proportion of aromatic compounds in the HC emissions ought to be high, and under cold-start conditions the temperature of the after-treatment system will not be sufficient to oxidise these heavy compounds. However, it was not possible to determine the precise influence of petrol composition on HC emissions, since emission levels were very low. For NO_x, the influence of aromatic content was similar to that for CO and HC. However, even though it was not possible to explain the results, fuel composition remains a key parameter for the evaluation of NO_x emission factors. Indeed, the NO_x emission factor for the Euro IV petrol fuel was always lower than that for the other petrol fuels. Similarly, no global trend could be identified for CO_2. Although the EPEFE equations have been validated on the test bench for NO_x emissions over the NEDC, the situation is clearly different regarding CO and HC, and more importantly the ARTEMIS cycles. The standard deviations over the ARTEMIS cycles were often too high to allow a clear comparison to be made. For NO_x slight changes in fuel composition (and physical characteristics) may affect the emissions. The Euro IV petrol fuel always resulted in the lowest levels for each pollutant. Its chemical and physical characteristics are well defined, and within a narrower range, than the fuels allowed for Euro III.

For the diesel fuels the results showed that over hot-start driving cycles CO emissions were very low, and there were no significant differences between the fuels. Over cold-start cycles, on the other hand, significant differences between fuels were observed. These results could not be explained in terms of fuel effects. The results were similar for HC. For NO_x, no significant influence of fuel was observed. However, in the case of PM, significant differences were observed between the fuels (**Figure B3-5**), but the repeatability was sometimes very poor. For CO_2, the fuel composition had a marginal influence on emissions. Therefore, in spite of some significant fuel impacts, especially for PM, it was considered inappropriate to propose any correction for taking into account the effects of fuel properties on emissions.

In the PARTICULATES project, a dedicated sampling and measurement system was employed in several laboratories in order to characterize the particle emissions of light-duty vehicles of various technologies, and using several fuels and a number of test cycles (Samaras *et al.*, 2005b). The only significant fuel effect observed was that of sulphur on the total particle number and particle surface area of diesel vehicles.

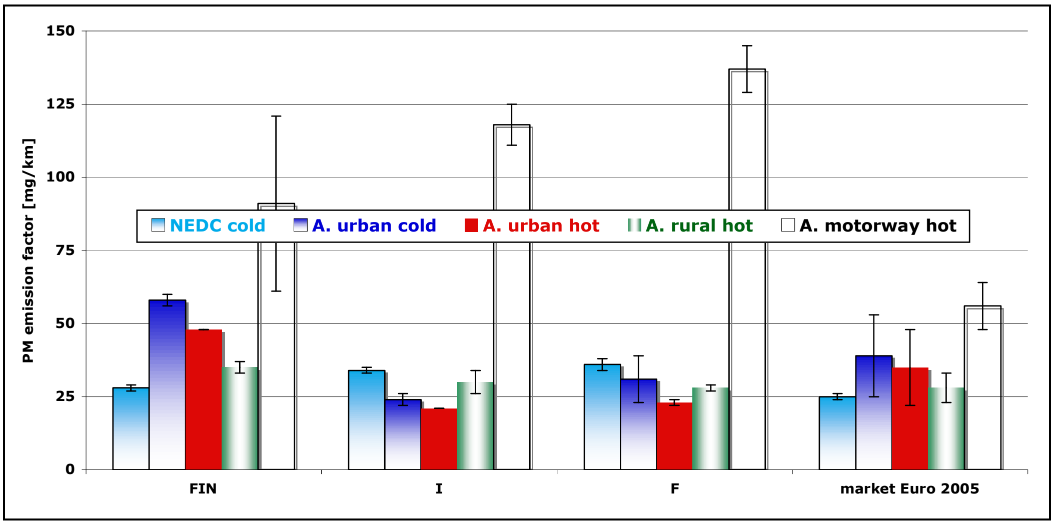

Figure B3-5: PM emission factors measured for one vehicle using four different diesel fuels and five different driving cycles.

Cooling fan operation

The effects of various cooling fan parameters were investigated using six cars over the ARTEMIS urban and rural driving cycles. The parameters included fan type, height above the ground, the control of the air speed (with or without roller speed dependence), and the position of the engine bonnet (closed or open). The cooling fan arrangement was varied using a small blower, conforming with standard emissions test protocols, set at a distance of 30 cm from the front of the car, and used both in the normal position (directed towards the front of the vehicle) or directed below the engine. In addition, a large blower with a 1.5 m^2 cross-sectional area and regulated air speed was employed. This was used either with fixed air speeds (30 or 60 km/h), or relative to the roller speed. In all tests the target ambient temperature was 23°C.

All the cars showed only small deviations (-3% to +2%) in CO_2 emissions, indicating a good basic level of reproducibility. However, the other exhaust components did not show any clear trends. The height of the small blower and the position of the bonnet had no significant effect on emissions. For petrol cars, a slight decrease in CO and NO_x emissions was generally noted when using the larger cooling fan and a higher air speed, compared with the normal fan, and a slight overall increase in HC emissions was observed with increased cooling power. In addition, diesel cars seemed to be less sensitive to the cooling arrangement than petrol cars. However, these trends were not consistent for all vehicles. Given the small number of cars tested, and the ambiguous nature of the results, it was concluded that correction factors for the effects of vehicle cooling fan arrangement could not be determined. However, a number of observations of the possible direction of the effects were noted, and these could serve as indicators in the overall evaluation of the sources of the disparity between the results obtained in different laboratories (Laurikko, 2005a).

Vehicle preconditioning

Vehicle preconditioning is required prior to emission tests in order to stabilise the thermal condition of the engine, exhaust after-treatment device, transmission, tyres and the dynamometer bearings. The effects of different preconditioning cycles were studied using five vehicles. The preconditioning cycles which were studied were 10 minutes of idling, 10 minutes at a constant speed of 80 km/h, the NEDC and the ARTEMIS urban driving cycle. The test protocol was as follows (i) a cold NEDC preconditioning cycle, (ii) a 10-minute delay with the engine switched off, (iii) the preconditioning cycle, and (iv) the measurement driving cycle, performed four times. The measurements were conducted at an ambient temperature of between

20°C and 25ºC, and local, commercial grade fuels were used (Olàh, 2005).

The results showed that preconditioning using the 10-minute idling cycle resulted in the largest emission values over all measurement cycles (Olàh, 2005). Emissions over the ARTEMIS rural cycle were influenced less by preconditioning than emissions over the ARTEMIS urban cycle. The emissions of diesel cars were influenced less by preconditioning than those of petrol vehicles. Emissions over the ARTEMIS urban cycle were most strongly influenced when the same cycle was used for preconditioning. The EUDC cycle as measurement cycle was influenced less by preconditioning than the other cycles (the first part of the NEDC cycle can be considered as a kind of preconditioning in itself). The method of preconditioning had no significant influence on emissions from modern closed-loop controlled vehicles with a catalyst.

The main conclusion of the work was that the 10-minute cycle at a constant speed of 80 km/h was the most suitable preconditioning cycle, as it resulted in the lowest emission levels and the lowest standard deviation for the majority of the measurements. Such a cycle is simple to conduct and is reproducible, and the length of the preconditioning can be modified without changing the cycle characteristic. The average engine load, temperatures and tyre temperature can be adjusted by changing the constant speed level.

B3.2.5 Vehicle sampling method

Method of vehicle sampling

The vehicle sampling methods used by the ARTEMIS laboratories included different types of random selection from car rental companies, private owners or car manufacturers. A survey was conducted to identify the terms used by the laboratories to characterise their sampling methods, and to describe the methods used for obtaining vehicles (André, 2002). The surveys revealed that the average number of vehicles in a given measurement campaign was between 10 and 25. The choice of the number of vehicles was determined principally from a financial perspective (cost of instrumentation, workforce, rent of vehicles, *etc.*). Other criteria included the representativeness of the sample, which is often determined using national or European statistics (*e.g.* sales, fleet composition, traffic), and the availability of the chassis dynamometer. The minimum number of vehicles below which laboratories do not consider the results as representative averages, or do not have confidence in their representativeness, is usually between three and ten per vehicle category (*e.g.* Euro II petrol cars >2.0 l). The representativeness of the sample is assessed according to several parameters, including (broadly in decreasing order of importance) fuel type, emission standard, engine technology, engine capacity, age, mileage and vehicle model. Some laboratories use statistical databases for assessing the representativeness of their sample according to these characteristics. The main approach for obtaining vehicles is via rental agencies, garages, dealerships or companies. Otherwise, vehicles can be selected from a list of private owners. In such cases, the owners are usually entitled to a financial incentive and a rental vehicle during the test period. Some laboratories pre-test vehicles, whereas others do not. All the laboratories rejected vehicles having serious defects.

Vehicle sample size

The influence of the sample size on the average emissions for the different vehicle types was studied via a statistical investigation of a database of emission measurements on 80 vehicles. The selected vehicles were representative of the French vehicle fleet, and were split into three vehicle categories: non-catalyst petrol, catalyst petrol, and non catalyst diesel. For each category, the minimum number of vehicles necessary to produce the same quality emission estimate as the maximum possible number of vehicles in the sample was determined. It was found that the minimum number of vehicles to obtain a representative emission factor or model for a given vehicle category usually exceeded 10 (Lacour and Joumard, 2001), and was around 12-13 for catalyst equipped vehicles.

B3.2.6 Laboratory-related parameters

Ambient temperature

Ambient temperature influences both cold-start and hot-start emissions, but the effects have rarely been studied over real-world driving cycles. In total, 31 passenger cars were tested over the ARTEMIS driving cycles. The tests were conducted at two separate laboratories: VTT and EMPA. Firstly, a cold-start test was performed, and when the engine was fully warmed-up, a hot-start test was performed. The ambient temperatures examined were -20°C, -7°C and 23°C.

Emissions of CO, HC, NO_x and CO_2 generally increased at lower ambient temperatures. However, in some cases a decrease in CO was detected, most notably in case of petrol-fuelled cars during rural and motorway driving. On average over all tested driving cycles, the ratio between emissions at -10°C and emissions at 20°C (based on regression) was for all tested petrol-fuelled cars (Euro II, Euro III and Euro IV) 0.96, 1.54, 1.11 and 1.05 for CO, HC, NO_x and CO_2 respectively, and for diesel Euro II cars the equivalent ratios were 2.14, 1.73, 1.04, 1.04, and 1.0 for PM. In general, the ratio was independent of the emission standard of the vehicle. However, for urban driving (*i.e.* low speed and low thermal load in the engine), HC emissions showed an increasing sensitivity to low ambient temperature with an advance in Euro standards (*i.e.* Euro IV cars were the most sensitive, and pre-Euro I cars were the least affected). The influence of ambient temperature on emissions was in most cases linear, but in a few cases (urban HC for petrol Euro IV, and motorway HC for diesel Euro II) an exponential type of function gave a better match (Laurikko, 2005b). In a few cases ambient temperature did not seem to have any effect.

Ambient humidity

The effect of ambient humidity on NO_x emissions is widely recognised, and a correction function is applied to all type approval measurements. However, the effect has only been studied for older types of vehicle. It was therefore necessary to update the NO_x correction function for modern vehicles, and to examine the effects on other pollutants. Emission tests were performed on eleven vehicles using a cell equipped with a humidification system to keep the humidity level within a specified range. In order to assess humidity levels outside the range deemed acceptable in type approval (5.5 to 12.2 g/H_2O per kg of dry air), the tests were conducted in winter when the ambient air was very dry. Additional water vapour was then added to the air to reach the 'normal' and 'above-normal' conditions (Laurikko, 2005c).

Some typical results for NO_x are given in **Figure B3-6**. The results are grouped for Euro II and Euro III petrol cars, and for diesel vehicles including both Euro levels. Both the individual test results and arithmetic mean values are plotted for each group under 'low', 'medium' and 'high' humidity conditions, and linear regression functions are fitted to the data. The results showed that an increase in ambient humidity lowered the NO_x emissions, which was the general trend expected from the humidity correction used in legislative testing. Over the ARTEMIS urban test cycle the standard correction was almost valid for diesel cars, with less than a 5% deviation. However, both groups of petrol cars would need a much larger correction, as the relative change over the allowed humidity range is about 35*%* for Euro II and over 55*%* for Euro III, and the standard factor gives a correction of only 20*%* within the same range of humidity. Therefore, the normalisation provided by the standard correction factor is insufficient. However, the situation is very different when rural driving is considered. All the linear correction models developed in ARTEMIS were similar, and the necessary correction was less than 20*%* (*i.e.* less than that provided by the standard method). Using the standard correction factor in this case actually led to a slight over-correction. However, the standard deviation of the pooled results for the urban cycle was two to three times higher than that of the results from the rural cycle. Therefore, the validity of the analysis was better for the rural case (Laurikko, 2005c).

There was hardly any correlation between petrol CO emissions, petrol Euro II HC emissions and the ambient humidity (correlation coefficients less than 0.2). For CO and HC emissions from diesel vehicles, correlation coefficient for CO and absolute humidity ranged from 0.60 (rural) to 0.73 (urban), and for HC ranged from 0.28 (urban) to 0.41 (rural). There was a clear influence of humidity on CO emissions from diesel cars and Euro II petrol cars during urban driving, and HC emissions from diesel cars, petrol Euro II cars and petrol Euro III cars during urban driving.

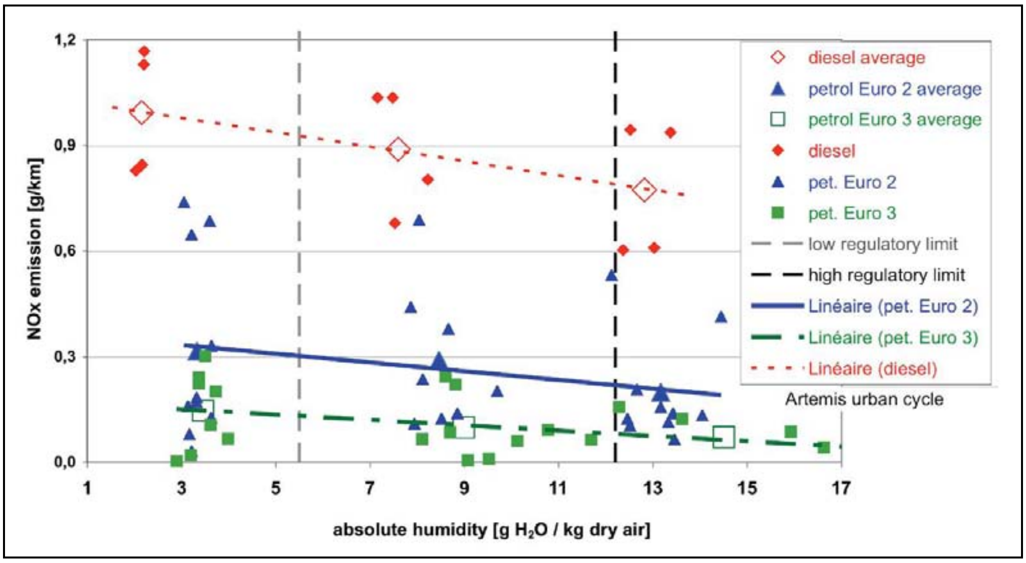

Figure B3-6: NO_x emissions over the ARTEMIS urban driving cycle as a function of ambient humidity. The lower and higher regulatory limits of humidity are also shown (*e.g.* EU directive 70/220/EEC).

Dynamometer settings

Emissions and fuel consumption are strongly dependent upon engine load. Hence, discrepancies in dynamometer load settings could affect emission and fuel consumption measurements. A questionnaire was sent to the laboratories participating in ARTEMIS in order to obtain information on the methods used to define dynamometer settings. It was assumed that the ARTEMIS laboratories were representative of other laboratories. Most of the laboratories either used road load information derived from coast-down tests or Directive EC70/220. The vehicle reference mass is determined either by weighing or by using information in registration documents. Two extreme chassis dynamometer settings and one average setting for static road load and vehicle inertia were defined. These three sets of settings were used to perform emission tests on five vehicles using the cold-start NEDC and the three hot-start ARTEMIS driving cycles (Vermeulen, 2005).

There was found to be a statistically significant effect of the dynamometer settings on CO_2 emissions and fuel consumption for both petrol and diesel cars. CO_2 and fuel consumption increased with an increase in road load. Deviations of -12% to -4% were observed for the minimum settings compared with the average settings. Deviations of +2% to +25% were observed for the maximum settings compared with the average settings. These ranges were observed for both petrol and diesel cars. The effect varied with the driving cycle. The efficiency of the complete drive line interferes at this point. Higher loads may cause higher drive line efficiency, for example. On the other hand the cycle characteristics determine the share of static and dynamic situations during the driving cycle. Because the relationships between the chassis dynamometer settings at different driving cycles and FC or CO_2 are not proportional, is recommended that the results should be considered as a range of uncertainty caused by worst-case chassis dynamometer settings.

For the regulated pollutants (CO, HC, NO_x and PM) no statistically significant influences were found. However, a clear trend was observed for NO_x emissions from diesel cars; the higher the road load settings the more NO_x the vehicles emitted. This was in line with expectations, as diesel engines commonly produce more NO_x when they operate at higher thermal loads. For CO emissions from petrol vehicles, an increase was observed over the ARTEMIS rural and motorway cycles using high road load settings, but again this effect was not significant. From the results of this investigation there were no clear indications that altered chassis dynamometer settings explicitly influenced the emissions of CO, HC, NO_x and PM, although from the theory it might be expected that a change in engine load will affect these emissions to some extent. The very small size of the vehicle samples (3 petrol, 2 diesel fuelled cars) does not allow a clearer conclusion.

It was found that chassis dynamometer settings may vary depending on the method chosen to determine the settings, the accuracy of the determination, and the variation of ambient conditions. Because for CO_2 (and fuel consumption) the effects of altered settings are significant, it is recommended that the methods used to determine the settings should be further investigated in order to identify systematic errors in CO_2 measurements (Vermeulen, 2005).

Dilution ratio

The dilution of the exhaust gases by non-polluted air forms the basis of the constant volume sampler. The dilution ratio varies according to the exhaust flow, but must remain within a limited range. The effects of changes in the dilution ratio were investigated for a total of eight diesel and petrol vehicles. Between two and five different dilution ratios were tested per vehicle. When the results were presented as a percentage deviation from the reference value - the emission value for the dilution ratio that would be normally selected for the respective measurement – no systematic trends were observed. The only notable exceptions were diesel PM emissions, for which there was a tendency towards higher emissions with an increase in the dilution ratio, and HC, for which the trend was in the opposite direction. The decrease in HC emissions may be attributed to increased condensation (which is measured as an increase in PM emissions) (Geivanidis *et al*., 2004).

Sample line temperature

For diesel vehicles the exhaust sample line must be heated to 190°C, according to the standard procedure, in order to avoid condensation of some hydrocarbons. The effects of a lower sample line temperature (160°C) were investigated. The lower temperature resulted in higher HC emission values, but this observation contradicted to what was expected, as the point of heating to the higher temperature is to increase the amount of HC maintained in the sample (Geivanidis *et al*., 2004).

PM filter preconditioning

A diesel passenger car was tested using PM filters preconditioned at different temperatures and humidity levels. The procedure consisted of reference tests with conditioning and weighing of the particle filters at an average temperature and humidity in a conditioning room, and emission tests with defined minimum and maximum values for these conditions. The minimum and maximum values were defined by the capability of the climate control system to adjust to a certain range of temperature and humidity. No effects of the filter preconditioning were observed, and all variations were within the repeatability ranges (Geivanidis *et al*., 2004).

Response time

The delay of emission measurements caused by the CVS system and the analysers is crucial for instantaneous measurements and second-by-second emission modelling, but also for standard HC measurements on diesel engines. As delay times may vary due to different concentrations, temperatures and pressures, the gas flow through the CVS system was modelled to determine a correction function which could be applied to the recorded emission measurements.

There are several potential problems associated with instantaneous emission measurement. The emission value recorded by an analyser is delayed and smoothed compared with the emission event at the point of formation due to (i) the transport of the exhaust gas to the analysers, (ii) the mixing of the exhaust gas, especially in the silencer and the CVS tunnel, and (iii) the response time of the analyser. The transport time of the exhaust gas to the analyser is determined by the velocity in the exhaust system of the vehicle, the CVS tunnel and the sampling lines. The velocity of the undiluted exhaust gas is highly variable over time, since it depends on the exhaust gas volume flow. The volume flow mainly depends on the engine speed and engine load. When combined, the varying transport times and the analyser response times can shift the signal by one to ten seconds. Mixing effects during the gas transport, as well as the analyser response behaviour, also have a smoothing effect on the signal. These inaccuracies are usually compensated over the complete test cycle, such that the integral of the instantaneous measurement agrees with the bag value. However, in most instantaneous emission models the mapping of emissions is performed by statically relating the emission signals to causative variables such as vehicle speed, vehicle acceleration and engine speed. As a result of this static approach, the emission values can be correlated to the correct engine state of the car only if they are at the correct location on the time scale. Thus, instantaneous models are heavily affected by inaccurate time alignments.

In order to minimise the errors resulting from inaccurate time alignments, EMPA and TUG developed separate methods to compensate the delay and smoothing of instantaneous emission measurements. Specially calibrated for the respective chassis dynamometers, both methods are designed to explain the change in the emission value from their location of formation to the analyser signal in terms of formulae, and to invert these formulae to obtain equations which transform the analyser signal into the engine-out (or catalyst-out) emission value (Le Anh *et al.*, 2005a). The main difference between the TUG and EMPA models is that the EMPA model is more detailed but needs modal measured data on the exhaust gas volume flow and information on the volume of the exhaust gas system of the tested cars. The TUG model has a simpler approach, which can be applied to the data normally recorded during dynamometer tests. Both methods proved to improve the quality of instantaneous emission signals significantly (Zallinger *et al.*, 2005; Joumard *et al.*, 2007).

As an example, **Figure B3-7** shows the oxygen signal at the catalyst outlet reconstructed from the analyser signal. The thick blue line is the concentration measured by a fast oxygen analyser *in situ* at the 'catalyst out' location. The thin red line is the concentration measured by a standard oxygen analyser attached to a 10 m-long raw gas line connected to the exhaust pipe of the car. The green dotted line is reconstructed from the red signal, compensating for the transport dynamics of the sampling line. The black dashed line is reconstructed from the green line, following compensation for the time-varying transport in the exhaust system of the car.

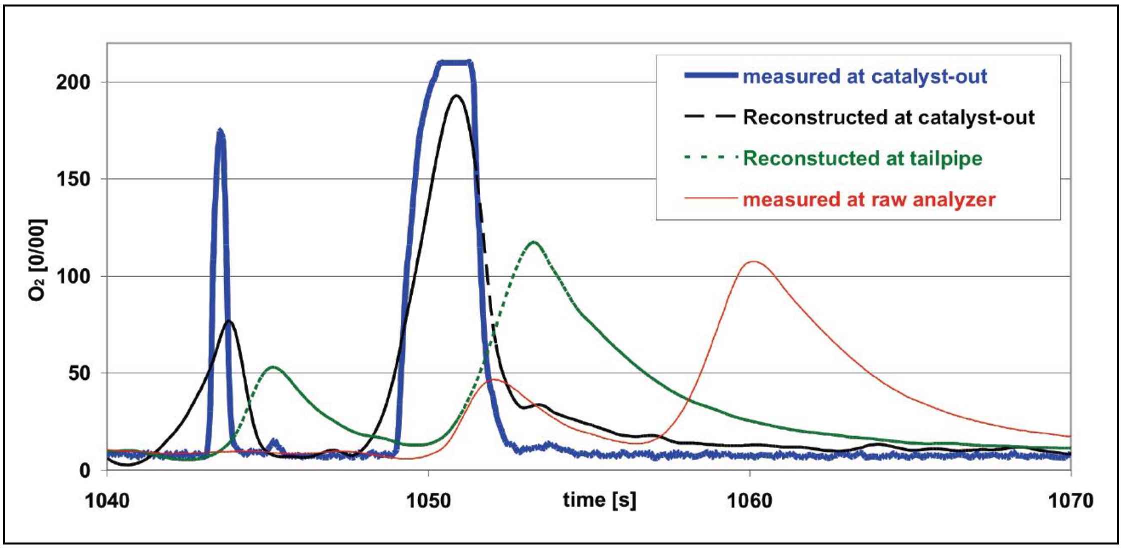

Figure B3-7: Overall inversion of the instantaneous concentration measured by a gas analyser, using the EMPA model.

Using signals from the diluted measurements, the quality of the reconstructed signals had a maximum time error of 2.5 seconds, which was significantly better than that of the original signal (25 seconds), but still notably worse than using the raw line. From **Figure B3-7** it is clear that using uncorrected signals from modal measurements leads to huge errors in the allocation of emissions to the corresponding engine operation conditions. Since the transport time of the undiluted part of the sample system depends on the exhaust gas volume flow, and thus on the engine load conditions, the misalignment between engine load and emission signal is highly variable over a test cycle. Thus, the constant time shift of measured signals used in previous models does not lead to a satisfactory results, but rather to distorted vehicle emission maps.

Dilution air conditions

Measurements with ambient dilution air were compared with measurements using two different levels of 'polluted' dilution air: a 'low' level and a 'maximum' level. The values considered as standard (0.4 ppm CO, 3-4 ppm HC, 0.1-0.2 ppm NO_x) were common to the participating laboratories. The 'low' level of polluted dilution air (2-3 ppm CO, 11-12 ppm HC, 1-1.2 ppm NO_x) was representative of the highest concentrations measured in ARTEMIS laboratories. The 'high' level of polluted dilution air represented an improbable state (11-12 ppm CO, 20-21 ppm HC, 5.5-6 ppm NO_x), which could only have occurred because of an incident such as a gas or fuel leak. In both cases, dilution air pollution was obtained by injecting a specific quantity of CO, HC and NO_x upstream of the dilution tunnel. For each of the three pollution levels, two repetitions of each cycle were performed. Two vehicles were tested over cold-start and hot-start driving cycles. The results showed that there were no statistically significant difference between the mean emission factors measured using the different types of dilution air (with the exception of HC emissions from one vehicle) (Prati and Costagliola, 2004).

B3.2.7 Round-robin tests

In the ARTEMIS round robin a single vehicle (a Euro III petrol car) was tested successively at the nine participating laboratories. The test schedule is shown in **Table B3-6**. The exercise lasted almost 8 months. The vehicle started the tour with a full fuel load, and the fuel was used continuously in the successive tests until the level became low, and then the vehicle was refuelled with the normal commercial fuel available locally (Laurikko, 2005d).

Table B3-6: Laboratory order, timing and fuels used during the Round-robin exercise, and number of tests over the full protocol.

Laboratory	Location	Country	Test period	Fuel	Number of tests
INRETS	Bron	F	27-07-2004 to 07-09-2004	Unleaded 95 RON	10
IM-CNR	Napoli	I	02-11-2004 to 04-11-2004	Unleaded 95 RON	3
TUG	Graz	A	16-11-2004 to 18-11-2004	Unleaded 95 RON	2
KTI	Budapest	H	02-12-2004 to 07-12-2004	Unleaded 95 RON	2
EMPA	Duebendorf	CH	13-12-2004 to 20-12-2004	Unleaded 95 RON (Migrol)	4
TNO	Delft	NL	28-12-2004 to 29-12-2004	RON 95, S<50ppm	2
MTC	Haninge	S	18-01-2005 to 19-01-2005	Blend 95, RVP 63	2
VTT	Espoo	FIN	27-01-2005 to 28-01-2005	Blend 95, RVP 63	2
LAT	Thessaloniki	GR	18-02-2005 to 24-02.2005	Unleaded 95 RON	3
INRETS	Bron	F	07-03-2005 to 11-03-2005	Unleaded 95 RON	5

The testing protocol determined the vehicle road load settings for the dynamometer, using either the coefficients of the basic road-load formula or the coast-down times (*i.e.* the time intervals between two pre-determined speeds on a free-rolling coast-down on the chassis dynamometer). As a further reference, the net power absorption at two speeds was also included. The test sequence was: (i) a cold NEDC, (ii) a hot NEDC, (iii) a hot ARTEMIS urban and (iv) a hot ARTEMIS rural (*i.e.* 6 bag samples in total), under normal ambient temperature conditions. At INRETS this complete protocol was executed ten times at the start of the round robin to examine emissions stability, between two and four times for the subsequent eight laboratories, and finally five times at INRETS at the end of the round robin. The exhaust emission test was augmented with stand-alone standard gas concentration measurements using a set of calibration gas samples which travelled with the vehicle. In addition, the temperature, humidity, barometric pressure and other data were collected to assist the analysis.

The best accuracy (lowest spread in results) was encountered for CO_2, for which the overall average deviation at each laboratory ranged between +7% and -10%, with an average coefficient of variation of around 5% (**Figure B3-8**). The next best was CO, for which the average spread ranged between +30% and -50%, and the average coefficient of variation was around 40%. For NO_x the figures were somewhat larger, between +60% and -35%, and average coefficient of variation below 40%. The highest spread by far was recorded for HC, for which the average deviation was between +120% and -50% compared with the average result of the whole group, and the average coefficient of variation was around 60%.

When comparing these variations with those values calculated on the basis of the repeat tests at INRETS, it was concluded that the overall variability recorded for CO over the whole round robin was roughly of the same order of magnitude as the 'basic' repeatability combining the repeatability of the laboratory and fluctuations in the car performance. However, with HC the overall spread of results was higher, suggesting that external factors, such as the change in fuel quality, affected and lowered the repeatability. For NO_x, the overall round-robin test variability was also somewhat higher than the basic value obtained from one laboratory alone, but the reasons for this were not known.

The round robin showed that assessing the variation between the measurements from different laboratories is not an easy task, and a quite large spread in the results was observed (Laurikko, 2005d). Two of the most influential factors were probably non-uniform fuel and variations in ambient test cell temperature. However, it also appeared that the emission behaviour of the car was not very stable, with poor repeatability. Therefore, part of the spread of results encountered in this exercise was probably a result of this vehicle variation, and not just the differences between laboratories.

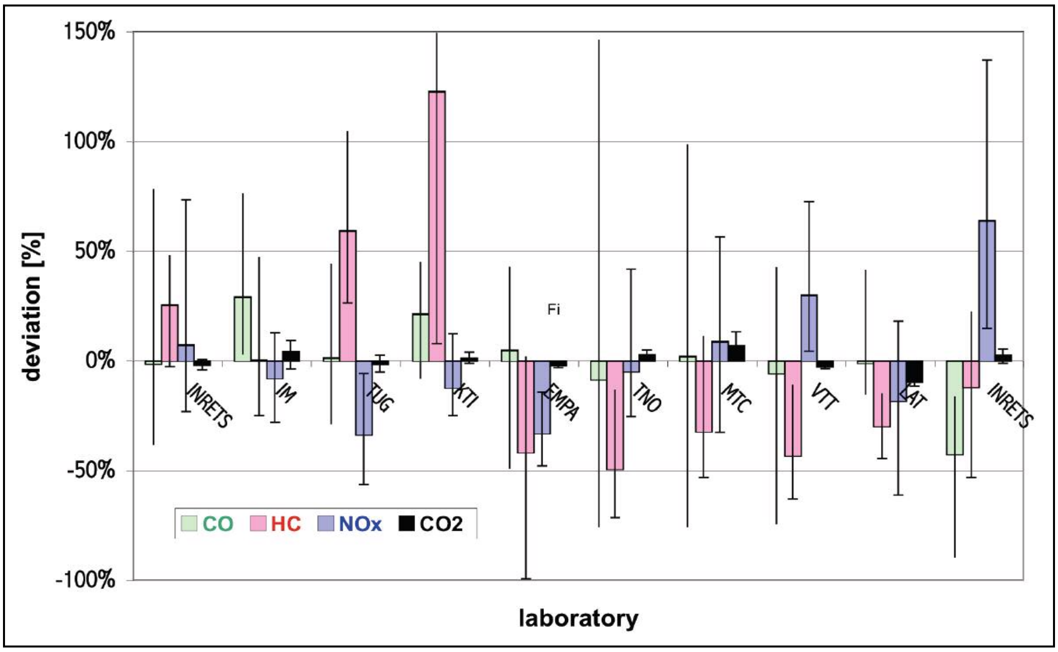

Figure B3-8: Relative emission deviation for each laboratory, in comparison with the average all laboratories considered (average for all cycles together for each component).

A closer assessment of the data revealed that it was not possible to develop any 'correction factor' or 'lab factor' which could be applied to the results provided by the laboratories to the pool of results collected in ARTEMIS. This conclusion was mainly based on two factors. The first of these was the time difference (over one year) between the round-robin exercise and the initial testing phase, which probably resulting in changes to the measurement apparatus, and in one case even a totally new set of main equipment (the CVS, analysers and chassis dynamometer were renewed at TUG). Therefore, it was probable that the results measured in this round robin exercise were different from those that would have been obtained if the round-robin test had been executed in parallel to the actual testing itself. However, this was not possible for a number of reasons. The second main factor was that when different driving cycles were used the spread of results became very random, and none of the laboratories showed consistently higher or lower results compared with the average. Laboratories could measure higher-than-average results for one driving cycle or pollutant, and lower-than-average results when another driving cycle or pollutant was considered. Only if each of the pollutants was considered separately could a few cases be found in which the results of a laboratory for that particular pollutant over all cycles tested was consistently higher or lower than the average.

B3.2.8 Summary and recommendations

The ARTEMIS passenger car study was designed to examine the influence of many different parameters on the measurement of emission factors. The main findings of the ARTEMIS work, and the implications of these findings, have been summarised below.

Effects of parameters

During the test programme, it was found that some parameters did not exert an influence over the measured emission factors. For other parameters, an influence was apparent, but could not be quantified. Finally, some parameters had a clear and quantifiable influence.

There was no statistically significant influence on emission measurements for the parameters listed in **Table B3-7**. This does not mean that these parameters have no influence on emission measurements, but only that an influence cannot be proved, taking into account the small data sample or the contradictory results. For parameters having a qualitative influence, recommendations are given in **Table B3 -8**.

In the case of parameters having a clear, statistically significant and quantifiable influence on the emission measurements. It was possible to normalise the emission measurements from different laboratories using correction factors. These parameters are listed in **Table B3-9**, and the quantitative correction factors are given on the pages which follow.

Table B3-7: Parameters having no influence on emissions.

Parameter	Findings	Recommendation
Vehicle-related parameters		
Emissions stability	The differences between the test results on several vehicles were larger than the differences obtained when testing the same vehicle several times.	A limited number of repeat tests should be conducted on each test vehicle, rather than taking a smaller sample of vehicles and using many repeat tests.
Fuel properties	In spite of there being significant differences, especially for PM emissions from diesel vehicles, it was not possible to propose an explanation based on current knowledge.	Common fuels should be used, rather than laboratory-specific fuels.
Cooling fan operation	Although the cooling arrangement did affect emissions, the results proved to be inconclusive. The position of the vehicle bonnet (either open or closed), the height of a small blower, and the cooling power (*i.e.* the flow of the cooling air) had no clear influence on emissions.	A high-power cooling system should be used in order to reproduce, as closely as possible, real-world cooling.
Laboratory-related parameters		
Sample line temperature	The observed emission changes contradicted what was expected from the physio-chemical properties of the diluted emissions.	None
PM filter preconditioning	No significant effects of filter preconditioning were observed.	None
Dilution air conditions	The quality of the dilution air had no significant influence on emission measurements	None

Table B3-8: Parameters having a qualitative influence on emissions.

Parameter	Findings	Recommendation
Driving cycle parameters		
Influence of the driver	Only CO_2 emissions were significantly higher with a human driver than with a robot driver, but the difference could not be explained by the driving characteristics. The robot did not give more stable emissions, and some driving cycles were too aggressive for it to follow.	A human driver can be used for emission tests, and tolerances of ± 2 km/h and ± 1 s should be applied. A test should be accepted if it is within these limits for > 99% of the time, and if the driven distance is within 1% of the reference distance. Notes should be made of failures due to insufficient power, wheel slip, a 'difficult' gearbox and, for the NEDC, if deceleration is more rapid than the reference, or if the engine stalls or does not activate immediately at test start. In all other cases a test should be rejected.
Vehicle-related parameters		
Technological characteristics	The type approval category and the fuel had a clear influence on emissions, and the engine capacity in some cases. No correlations between emission behaviour and specific emission control technologies were found within the same type approval category.	The addition of specific technological characteristics to models will not improve the accuracy of emission databases for cars up to Euro IV
Vehicle preconditioning	The preconditioning had an influence on emissions in some cases, but rarely for modern closed-loop vehicles.	A 10-minute cycle at a constant speed of 80 km/h can be considered as the most suitable preconditioning cycle.
Vehicle sampling method		
Method of vehicle sampling		Where possible, test vehicles should be selected from an 'official' list, avoiding vehicles of the laboratory staff. The real-world distributions of fuels, emission standards, vehicle sizes, maximum engine power and mileage should be taken into account in the selection of vehicles.
Vehicle sample size	The variability between vehicles and the emitter status are significant factors. It is not possible to know the emitter status before measurement, and the high variability between vehicles within a category requires that cars are sampled randomly.	A minimum sample of 10 vehicles should be used to derive emission factors for a given vehicle category which are representative of average emission behaviour.
Laboratory-related parameters		
Dynamometer settings	The dynamometer settings have a clear influence on emissions, but are only significant for CO_2 and fuel consumption, and NO_x for diesel vehicles.	Measurements conducted using altered chassis dynamometer settings should not be used to derive emission factors. For emission factor development, road load information derived from the coast-down method performed by the laboratory and inertia setting should be as close to the on-road values as possible.
Response time		For the development of instantaneous emission models, the emission signal must be corrected for dynamic distortion during measurement.

Table B3-9: Parameters having a quantitative influence on emissions.

Parameter	Findings	Recommendation
Driving cycle parameters		
Driving cycle	The analyses demonstrated the significant influence of the driving cycle on emissions. However, it was not possible to determine a systematic correction. Given the great diversity of the emission data collected in ARTEMIS, and the large range of driving cycles, the cycle influence was taken into account for the development of the emission factors. A classification system was developed, based on the similarities between cycle kinematics, which enabled the computation of emissions for detailed types of driving.	It is highly recommended that passenger cars should be tested using real-world driving cycles, such as the ARTEMIS urban, rural and motorway cycles, or cycles adapted to vehicle performance.
Gear-shift behaviour	It was possible to classify gear-shift strategies according to CO_2 emissions (the only pollutant systematically affected). The gear-shift strategy affected CO_2 emissions by between 2% and 18%. The most polluting strategy was one in which gear changes were defined for given engine speeds. The least polluting strategy was one in which gear changes were defined for given vehicle speeds.	The gearshift strategy used in the ARTEMIS and vehicle-adapted driving cycles, which is dependent upon the vehicle power-to-mass ratio and the 3rd gear ratio, seems to be the most appropriate.
Vehicle-related parameters		
Vehicle mileage	The influence of mileage on petrol vehicle emissions depended on the pollutant, the emission standard and the average speed. Mileage had no influence on CO_2 emissions, but increased CO, HC and NO_x emissions from petrol cars. Between 0 km and 100,000 km, emissions of these pollutants increased by a factor of 3.6 on average for Euro I and II vehicles, and by 15% for Euro III and IV vehicles. No mileage effect was observed for diesel vehicles. No effect of maintenance was observed on the emission level, either as a consistent before-after maintenance improvement or as a function of mileage.	
Laboratory related parameters		
Ambient temperature	An ambient temperature effect was observed for all pollutants and most vehicle classes. Hot exhaust emissions decreased with increasing temperature for petrol and diesel cars, but more so for diesel cars.	It is recommended that tests should be conducted at an ambient air temperature close to the real-world average.
Ambient humidity	The influence of ambient humidity was observed only for NO_x and then only for some vehicle classes. Between the low and high regulatory limits of humidity (5.5 and 12.2 gH_2O/kg dry air), NO_x emissions decrease for petrol and diesel vehicles by 30% and 15% respectively. This humidity effect was different from the legislative correction factor kH.	It is recommended that test are performed at an ambient air humidity close to the real-world average.
Dilution ratio	A higher dilution ratio only increased diesel PM emissions.	

Correction factors

The influence of five parameters could therefore be quantified (i) gear-shift behaviour, (ii) vehicle mileage, (iii) ambient air temperature, (iv) ambient air humidity, and (v) exhaust gas dilution ratio. Correction factors were derived for the first four of these.

Gear-shift behaviour

The correction factor (***CF***) is used for CO_2 according to the formula:

$$\boldsymbol{CF = \frac{emission\ CO_2\left(Artemis\ strategy\right)}{emission\ CO_2\left(other\ strategy\right)}} \qquad \text{(Equation B3-2)}$$

For all driving cycles other than the NEDC, ***CF*** is equal to one. For the NEDC, the values of ***CF*** for the ARTEMIS rural and motorway cycles are 1.08 and 1.03 respectively.

Vehicle mileage

The influence of the mileage M_1 or M_2 (km) is expressed by the formula:

$$\frac{emission(M_1)}{emission(M_2)} = \frac{y(M_1)}{y(M_2)}$$ (Equation B3-3)

Values of ***y*** are given for Euro I and II petrol cars in **Table B3-10**, and for Euro III and IV petrol cars in **Table B3-11**, in both cases for urban and rural situations (average speeds lower than 19 km/h and higher than 63 km/h respectively). For an intermediate speed, ***V***, the following formula is used:

$$y(V) = y(urban) + \frac{(V-19)\cdot(y(rural) - y(urban))}{44}$$ (Equation B3-4)

Table B3-10: Emission degradation correction factor **y** = **a** x ***Mileage*** + **b**, for Euro I and Euro II petrol vehicles. Mileage expressed in km, ***y*** normalised for the corresponding average mileage.

Petrol Euro I and II		Engine capacity (l)	Average mileage (km)	***a***	***b***	Value at ≥ 120,000 km
y (urban) for ***V***≤19 km/h	CO	≤1.4	29,057	1.523E-05	0.557	2.39
		1.4-2.0	39,837	1.148E-05	0.543	1.92
		>2.0	47,028	9.243E-06	0.565	1.67
	HC	≤1.4	29,057	1.215E-05	0.647	2.10
		1.4-2.0	39,837	1.232E-05	0.509	1.99
		>2.0	47,028	1.208E-05	0.432	1.88
	NO_x	All	44,931	1.598E-05	0.282	2.20
y (rural) for ***V***≥63 km/h	CO	≤1.4	29,057	1.689E-05	0.509	2.54
		1.4-2.0	39,837	9.607E-06	0.617	1.77
		>2.0	47,028	2.704E-06	0.873	1.20
	HC	≤1.4	29,057	6.570E-06	0.809	1.60
		1.4-2.0	39,837	9.815E-06	0.609	1.79
		>2.0	47,028	6.224E-06	0.707	1.45
	NO_x	all	47,186	1.220E-05	0.424	1.89

Table B3-11: Emission degradation correction factor ***y*** = ***a*** *x* ***Mileage*** + ***b***, for Euro III and Euro IV petrol vehicles. Mileage expressed in km, ***y*** normalised for the corresponding average mileage.

Petrol Euro III and IV		Engine capacity (l)	Average mileage (km)	***a***	***b***	Value at ≥ 160,000 km
y (urban) for ***V***≤19 km/h	CO	≤1.4	32,407	7.129E-06	0.769	1.91
		>1.4	16,993	2.670E-06	0.955	1.38
	HC	≤1.4	31,972	3.419E-06	0.891	1.44
		>1.4	17,913	0	1	1
	NO_x	≤1.4	31,313	0	1	1
		>1.4	16,993	3.986E-06	0.932	1.57
y (rural) for ***V***≥63 km/h	CO	≤1.4	30,123	1.502E-06	0.955	1.20
		>1.4	26,150	0	1	1
	HC	all	28,042	0	1	1
	NO_x	all	26,150	0	1	1

Ambient air temperature

The influence of the temperature T_1 or T_2 (°C) is expressed by the formula:

$$\frac{emission(T_1)}{emission(T_2)} = \frac{y(T_1)}{y(T_2)}$$ (Equation B3-5)

Values of ***y*** are given for urban, rural and motorway driving behaviour in **Table B3-12**.

Table B3-12: Correction factor $\boldsymbol{y} = \boldsymbol{a} \times \boldsymbol{Temperature} + \boldsymbol{b}$, or $\boldsymbol{y} = \boldsymbol{a}\ e^{\boldsymbol{b.Temperature}}$ when in italics, for urban, rural or motorway driving behaviour. Temperature in °C, ***y*** normalised at 23°C.

Pollutant	Fuel	Emission category	Urban		Rural		Motorway	
			a	***b***	***a***	***b***	***a***	***b***
CO	Petrol	Pre-Euro I	0.0021	0.95	0.003	0.93	0.0054	0.88
		Euro II	-0.0115	1.3	0.002	0.95	-	-
		Euro III	-0.0087	1.2	0.0053	0.88	-0.0008	1.02
		Euro IV	No correction		0.017	0.61	-	-
	Diesel	Euro II	-0.034	1.784	-0.075	2.72	-0.024	1.56
HC	Petrol	Pre-Euro I	-0.001	1.02	-0.0027	1.066	No correction	
		Euro II	-0.016	1.37	No correction		-	-
		Euro III	-0.0525	2.21	-0.025	1.57	-0.001	1.02
		Euro IV	*3.4627*	*-0.0544*	0.0107	0.7442	-	-
			$y = a\ e^{bT}$				$y = a\ e^{bT}$	
	Diesel	Euro II	-0.027	1.62	-0.032	1.75	*1.43*	*-0.015*
NOx	Petrol	Pre-Euro I	-0.0075	1.17	-0.0063	1.14	-0.0035	1.08
		Euro II	-0.0091	1.21	0.0045	0.895	-	-
		Euro III	-0.0084	1.19	-0.0027	1.065	-0.002	1.05
		Euro IV	-0.01	1.23	0.0013	0.97	-	-
	Diesel	Euro II	-0.0015	1.05	-0.0015	1.05	-0.0006	1.016
CO_2	Petrol	Pre-Euro I	-0.0038	1.09	-0.0038	1.09	-0.0033	1.08
		Euro II	-0.0013	1.03	-0.0017	1.04	-	-
		Euro III	-0.001	1.03	-0.0013	1.03	-0.0015	1.0342
		Euro IV	-0.0028	1.0619	-0.0016	1.0334	-	-
	Diesel	Euro II	-0.0015	1.03	-0.0017	1.04	-0.0009	1.0205
PM	Diesel	Euro II	0.005	0.88	No correction		-0.005	1.11

Ambient air humidity

The influence of the humidity on NO_x emission is expressed by the formula:

$$\frac{\boldsymbol{emission}(\boldsymbol{H}_1)}{\boldsymbol{emission}(\boldsymbol{H}_2)} = \frac{\boldsymbol{y}(\boldsymbol{H}_1)}{\boldsymbol{y}(\boldsymbol{H}_2)} \quad \text{(Equation B3-6)}$$

Values of ***y*** are available for some vehicle classes and for urban and rural driving behaviour in **Table B3-13**. It is recommended that the rural values are used for motorway driving behaviour, that the petrol Euro II values are used for petrol pre-Euro I and Euro I, that the petrol Euro III values are used for petrol Euro IV, and that the diesel Euro II values are used for the other diesel vehicles. For other pollutants, no correction factors are proposed.

Table B3-13: Correction factor $\boldsymbol{y} = \boldsymbol{a} \times \boldsymbol{Humidity} + \boldsymbol{b}$, for uncorrected or corrected NO_x emissions using the current method, and for urban or rural driving behaviour. ***Humidity*** in g H_2O/kg dry air, ***y*** normalised at 10.71 g H_2O/kg dry air.

	Fuel	Emission category	Urban		Rural	
			a	***b***	***a***	***b***
Uncorrected emissions	Petrol	Euro II	-0.052	1.5592	-0.0293	1.31
		Euro III	-0.081	1.8669	-0.0284	1.3
	Diesel	Euro II	-0.0249	1.2668	-0.0307	1.325
Corrected emissions	Petrol	Euro II	-0.0182	1.1944	0.004	0.9571
		Euro III	-0.0529	1.5654	-0.0093	1.0996
	Diesel	Euro II	0.0067	0.9281	0.0106	0.8869

Exhaust gas dilution ratio

The dilution ratio (between exhaust air and dilution air), the quality of the dilution air and the PM filter preconditioning do not appear to have clear influence on emissions. A correction factor could be determined for PM, but could not applied to the common ARTEMIS emission data, as the dilution ratio was usually unknown.

Data management

The following basic recommendations are provided for the future management of European emissions data (*i.e.* the way in which data are recorded and pre-processed) (Joumard *et al*., 2006):

- Vehicle characteristics and usage conditions should be recorded precisely as described above (driving cycle characteristics, ambient air, cooling), especially when these conditions are specific to the country/laboratory.
- No correction factors should be applied to the measured parameters by the testing laboratory, especially for humidity.
- Data should be entered into the ARTEMIS LVEM database (see Section B3.5).
- The correction factors proposed in Section B3.3.2 should be applied to the data in the ARTEMIS LVEM database in order to harmonise the data.

B3.3 Improvement of the emission factor database

B3.3.1 Effects of gradient and vehicle load

Engine power demand is a decisive parameter for vehicle emissions and fuel consumption, and the power demand is dependent upon the resistance to motion. A positive road gradient (uphill) increases the driving resistance of a vehicle, and a negative road gradient (downhill) decreases it. However, the additional emissions associated with a positive road gradient are not compensated by the lower emissions associated with a negative road gradient (Hassel *et al.*, 1994). Engine power demand is also increased by increasing the vehicle load, although the increase in the power demand due to vehicle load is less than the increase due to a positive road gradient. In fact, it is not certain that emissions will increase with increasing vehicle load, as the exhaust after-treatment system may be working more effectively.

Although emission measurements have been made over driving cycles with different road gradients, they do not cover the more recent vehicle technologies. For current and near-future vehicles, new data were therefore required. In ARTEMIS, new measurements were carried out for the typical range of European gradients and payloads. The numbers of measurements were, however, too small to obtain emission factors for all driving and gear shift situations, and the results were only valid for the specific test conditions. Gaps in the data were therefore filled by modelling. A more detailed description is available in the report by Zallinger and Hausberger (2004).

Measurements

Road gradient

Because of the small sample and the different vehicles (engine power and capacity) in the sample, an average emission for diesel and petrol vehicles could not be calculated for each different road gradient. Instead, the ratio between the emission value measured at a given gradient and that measured at 0% gradient was determined for every test, and then the average ratios for the varying road gradients were calculated for diesel and petrol vehicles:

$$Road\ gradient\ factor = \frac{Emissions\ at\ x\%\ road\ gradient}{Emissions\ at\ 0\%\ road\ gradient} \qquad \text{(Equation B3-7)}$$

The fuel consumption, CO and HC road gradient factors for petrol vehicles showed a progressive increase with an increase in gradient, but for NO_x no pattern was evident. For NO_x, PM and fuel consumption from diesel vehicles there was a progressive increase in the road gradient factor with an increase in gradient, whereas for CO and HC there was no discernible pattern. The emission levels of CO and HC from diesel engines were low, and therefore a small difference in the measured values for a road gradients had a large influence on the corresponding gradient factor.

Vehicle load

A similar approach was adopted for vehicle load. The common measurement situation (analogous to 0% road gradient) was ‘vehicle with driver and unloaded’. The ‘loaded’ situation involved measurement at the full payload (on average, 450 kg), and the ‘half loaded’ situation was half way between ‘unloaded’ and ‘loaded’.

$$Loading\ factor = \frac{Emissions\ with\ load}{Emissions\ with\ 90[kg]\ load}$$ (Equation B3-8)

For petrol vehicles it was only possible to generate a loading factor for fuel consumption, as the influence of vehicle load on pollutant emissions had the same range as the standard deviation of the repeatability tests. For emissions of NO_x and PM (and fuel consumption) from diesel vehicles the vehicle load had a clear influence, and therefore it was possible to generate loading factors for these pollutants. For HC and CO, loading factors could not be determined (Joumard *et al.*, 2007). From the measurements, the final correction factors for diesel vehicles (FC, NO_x and PM) and petrol vehicles (FC) were calculated using an average loading situation (1.5 persons per vehicle).

Comparisons with other sources of data

Road gradient

For road gradient, comparisons were made between the factors based on the ARTEMIS measurements and those from two other sources of data. One of these sources was the Handbook of Emission Factors (HBEFA) (Keller, 2004), in which the road gradient factors are based on measurements on pre-Euro I and Euro I vehicles (Hassel *et al.*, 1994). The other source was the instantaneous emission model PHEM, which was developed within ARTEMIS (Rexeis *et al.*, 2005). Using HBEFA, emission factors can be obtained for road gradients from -6% to +6%. For this comparison a rural cycle (AO_HVS3) was chosen, with an average speed in the same range as that of the measured cycle.

In the case of petrol vehicles, the agreement between the ARTEMIS and HBEFA factors was quite good for fuel consumption and CO. For HC and NO_x emissions the agreement was worse. However, for HC the calculated average road gradient factor was in the same range as the HBEFA factor. In the case of diesel vehicles, for fuel consumption and PM mass the agreement between the HBEFA factors and those based on the ARTEMIS measurements was very good, whereas for NO_x, especially for the larger positive gradients, it was worse. This disagreement can perhaps be explained by the different gearshift strategies used in HBEFA and the measurements, and in the differences between the driving cycle speed. A reasonable technical explanation may be that the ARTEMIS Euro III cars had exhaust gas recirculation (EGR) to lower NO_x emissions, and that this is not active at the high engine loads and engine speeds which occur frequently at high road gradients. The cars measured for HBEFA did not have EGR. For CO and HC the ARTEMIS measurements produced higher gradient factors than HBEFA.

The comparison with PHEM was performed for Euro III vehicles using the ARTEMIS rural cycle for 0, ±2% and ±4% road gradients. For ±6%, ±8% and ±10% road gradients the average velocity of the driving cycle was adapted (*i.e.* decreased) to match the average velocity of the HBEFA cycles. The acceleration was also decreased, which seemed to be a logical approach for higher road gradients. Average engine emission maps of 8 petrol and 7 diesel Euro III vehicles were used as input to PHEM. For petrol vehicles, the emissions of CO and HC (and fuel consumption) predicted by PHEM agreed well with the measurements. The agreement for NO_x was poor. For diesel vehicles the emissions of NO_x and PM (and fuel consumption) predicted by PHEM showed a good agreement with the ARTEMIS measurements, except for the higher road gradients. The comparison for HC also showed a good agreement, but for CO the result was worse. In summary, PHEM reproduced the ARTEMIS measurements over a wide range of road gradients, with a good level of agreement for both petrol and diesel vehicles. PHEM is therefore a useful tool for generating emission factors for other traffic situations.

Vehicle load

Because of the small vehicle sample a comparison with other sources of data was necessary to evaluate the influence of load on emissions and fuel consumption.

In a study by INRETS, 27 diesel light commercial vehicles were tested on a chassis dynamometer using different driving cycles and load levels (Joumard *et al.*, 2003). The vehicles complied with the following European emission standards: 88/436 (1 vehicle), Euro I (7 vehicles) and Euro II (19 vehicles). The mileage and age of the vehicles varied significantly from one category to another. For light vans the load generally led to a decrease in emissions, which was small for gaseous pollutants (-2% to -7% depending on the pollutant) but more marked for PM (-20 %). For heavier vans the load had a mixed effect, depending on the pollutant. For 2.5-tonne vans the load has a very clear influence on CO and HC emissions (an average decrease of one third, and even more in urban traffic) and only a slight influence on PM (-8 %). For NO_x and CO_2 the load systematically increased the emissions by 10% to 20%, whatever the speed. For 3.5-tonne vans the load decreased HC and PM emissions by -10% to -15%, had practically no influence on CO emissions, and considerably increased CO_2 emissions (+14%, regardless of the average speed) and NO_x emissions (+44%, and even more in extra-urban areas). However, as this study dealt with light commercial vehicles any comparisons with passenger cars should be viewed with caution, as the mass ratio between the unloaded and loaded vehicle is substantially different.

PHEM was again run to give emission factors for Euro III vehicles, both loaded and unloaded, and hence a loaded/unloaded factor. For the calculation of three different driving situations (urban, rural and motorway) the ARTEMIS cycles were used. In the case of diesel vehicles, for NO_x, PM and fuel consumption the agreement between the loading factors derived from the PHEM predictions and the measurements was good (see **Figure B3-9**). The agreement for CO was poor (the 'unloaded' emission was very low, and therefore the factor was very high). Furthermore, the repeatability for CO tended to be low (Joumard *et al.*, 2006), and the measurements involved only two vehicles without cycle repetition. For petrol Euro III vehicles, PHEM only showed a good agreement with the FC measurements. The repeatability for petrol vehicle emissions was worse than that for diesel vehicles, and accurate loading factor s could not be derived from the small number of tests conducted.

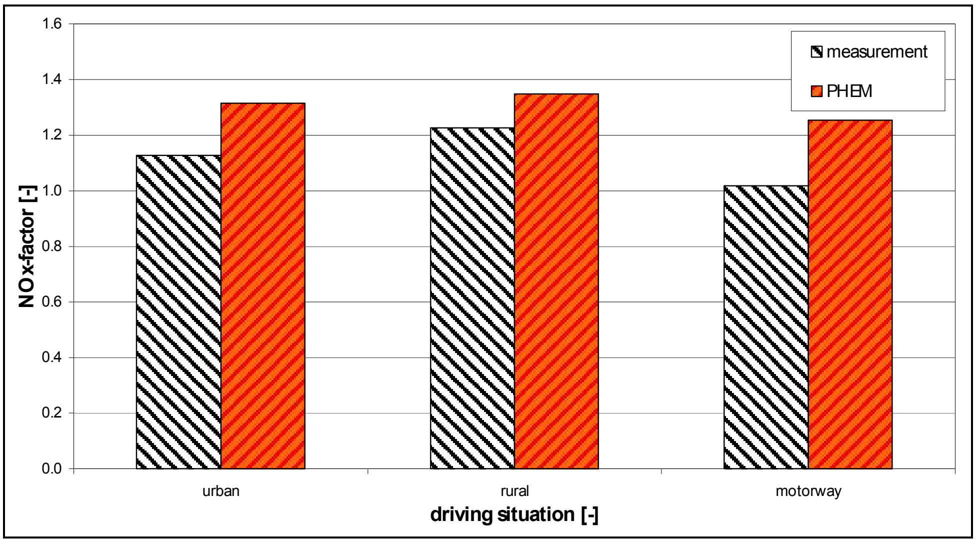

Figure B3-9: Loaded/unloaded factors for different driving situations, diesel Euro III vehicle and NO_x.

Combination of road gradient and vehicle loading

For reasons of economy, no tests were performed with different loads and gradients, but nevertheless it was important to determine whether the influence of the vehicle weight is stronger at higher road gradients. To assess the influence of vehicle load at different road gradients, the ARTEMIS urban, rural and motorway cycles were simulated using PHEM, with varying vehicle payload (unloaded, half loaded and loaded) for both average diesel and petrol Euro III vehicles.

For diesel vehicle emissions (NO_x and PM) and fuel consumption, the PHEM simulation indicated a minor influence of vehicle load, as was expected for higher road gradients (see **Figure B3-10**). For CO and HC, the factors were too sensitive to make a statement about the influence of the load level. The influence of the loading level on the emissions and fuel consumption of petrol vehicles was more or less the same at different road gradients. The influence of loading at higher road gradients only increased for NO_x emissions, but this is not particularly important as emission levels are quite low. Higher road gradients (>8 %) could not be simulated with the common engine map generated from the ARTEMIS cycles.

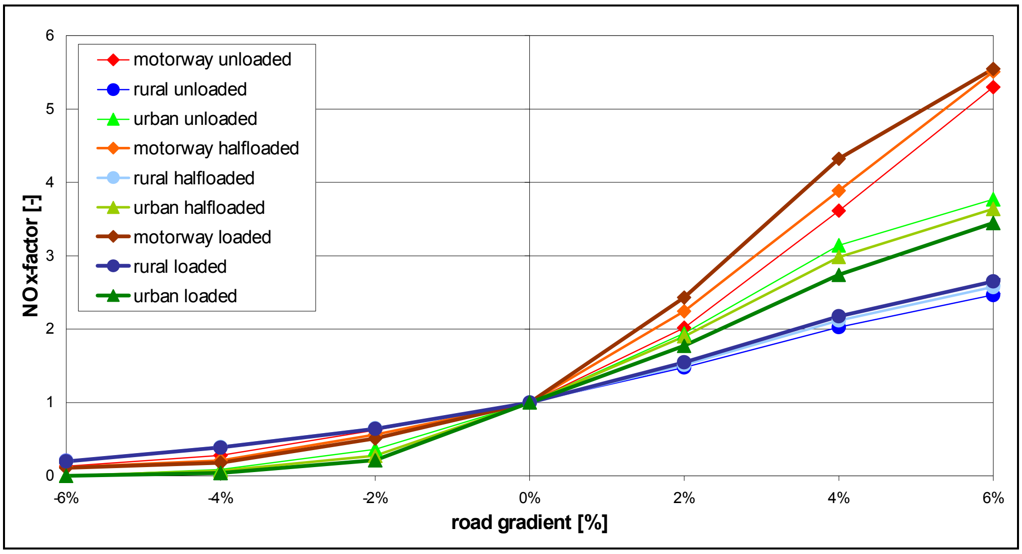

Figure B3-10: Combined road gradient and load factors for Euro III diesel vehicles and NO_x.

Final correction factors

To extend the database of road gradient emission factors to other traffic situations and emission standards, the factors for the final ARTEMIS database were simulated using PHEM. A vehicle load correction was also proposed for fuel consumption, NO_x and PM mass for diesel vehicles, and for fuel consumption for petrol vehicles.

Road gradient

The cycle for the motorway driving situation was recorded on a hilly motorway in Austria, and covered a wide range of road gradients (-6% to 6 %). For the rural driving situation, the ARTEMIS rural cycle was used. The urban driving situation was simulated using one of the Handbook driving cycles at different road gradients. As described above, some adjustments to the driving cycles were made.

For all European emission regulations (Pre-Euro I to Euro IV), diesel and petrol car engine maps were obtained for the simulation from the available measurements. Unfortunately, no Euro I and Euro II petrol vehicles were measured over the ARTEMIS cycle. Consequently, the factors for petrol vehicles were the same for pre-Euro I and Euro I. In addition, the Euro II factors were the same as those for Euro III. Similarly, for diesel vehicles the Euro IV factors were the same as those for Euro III. With these adjustments, the final road gradient factors for the ARTEMIS database were calculated using PHEM (**Tables B3-14** to **B3-18**).

Table B3-14: Road gradient factors for Pre-Euro I diesel and petrol vehicles (factor = 1 at 0% gradient).

	Gradient	Diesel vehicle					Petrol vehicle			
		FC	NO_x	HC	CO	PM	FC	NO_x	HC	CO
Urban	2%	1.241	1.345	0.981	1.037	1.083	1.129	1.359	1.048	1.099
	-2%	0.773	0.692	1.006	0.971	0.921	0.869	0.689	0.968	0.910
	4%	1.534	1.783	0.995	1.067	1.263	1.291	1.883	1.128	1.203
	-4%	0.578	0.453	1.035	0.953	0.876	0.767	0.490	1.013	0.842
	6%	1.902	2.382	1.045	1.655	1.550	1.460	2.459	1.176	1.277
	-6%	0.386	0.265	0.918	0.814	0.699	0.680	0.332	1.015	0.775
Rural	2%	1.308	1.424	0.975	1.109	1.156	1.183	1.335	1.111	1.281
	-2%	0.818	0.735	1.292	1.153	1.165	0.868	0.759	0.951	0.793
	4%	1.656	1.897	0.958	1.129	1.384	1.381	1.699	1.263	1.656
	-4%	0.577	0.451	1.293	1.105	1.043	0.699	0.494	0.962	0.675
	6%	2.065	2.448	1.112	1.097	1.819	1.576	2.001	1.424	1.956
	-6%	0.321	0.214	1.043	0.836	0.686	0.582	0.302	1.046	0.595
	8%	2.437	2.888	1.280	1.316	2.102	1.827	2.475	1.656	1.935
	-8%	0.174	0.085	1.109	0.839	0.610	0.529	0.147	1.191	0.576
	10%	2.905	3.325	1.821	1.897	2.609	2.070	2.569	1.981	1.755
	-10%	0.109	0.046	0.994	0.726	0.471	0.481	0.097	1.132	0.528
Motorway	2%	1.354	1.485	0.885	0.874	1.180	1.248	1.148	1.323	1.791
	-2%	0.663	0.584	1.127	1.206	0.790	0.775	0.748	0.754	0.554
	4%	1.667	1.946	0.824	0.974	1.278	1.432	1.278	1.571	2.192
	-4%	0.339	0.218	1.130	1.131	0.588	0.564	0.394	0.620	0.360
	6%	2.057	2.620	0.810	0.946	1.578	1.703	1.546	1.856	2.887
	-6%	0.134	0.047	1.074	0.975	0.474	0.416	0.194	0.587	0.282

Table B3-15: Road gradient factors for Euro I diesel and petrol vehicles (factor = 1 at 0% gradient).

	Gradient	Diesel vehicle					Petrol vehicle			
		FC	NO_x	HC	CO	PM	FC	NO_x	HC	CO
Urban	2%	1.243	1.368	0.961	1.025	1.124	1.1287	1.3586	1.0477	1.0985
	-2%	0.771	0.674	1.029	0.983	0.878	0.8688	0.6886	0.9683	0.9096
	4%	1.537	1.829	0.965	1.054	1.346	1.2907	1.8826	1.1282	1.2035
	-4%	0.576	0.425	1.085	0.980	0.789	0.7672	0.4900	1.0129	0.8421
	6%	1.905	2.451	1.008	1.633	1.670	1.4604	2.4592	1.1759	1.2767
	-6%	0.384	0.241	0.984	0.846	0.581	0.6796	0.3315	1.0154	0.7752
Rural	2%	1.309	1.443	0.930	1.089	1.205	1.183	1.335	1.111	1.281
	-2%	0.816	0.711	1.396	1.216	1.089	0.868	0.759	0.951	0.793
	4%	1.658	1.932	0.882	1.098	1.474	1.381	1.699	1.263	1.656
	-4%	0.574	0.423	1.439	1.183	0.918	0.699	0.494	0.962	0.675
	6%	2.067	2.488	1.051	1.084	1.923	1.576	2.001	1.424	1.956
	-6%	0.319	0.198	1.190	0.897	0.529	0.582	0.302	1.046	0.595
	8%	2.439	2.939	1.210	1.307	2.226	1.827	2.475	1.656	1.935
	-8%	0.172	0.074	1.315	0.922	0.390	0.529	0.147	1.191	0.576
	10%	2.907	3.375	1.779	1.906	2.711	2.070	2.569	1.981	1.755
	-10%	0.108	0.039	1.209	0.805	0.245	0.481	0.097	1.132	0.528
Motorway	2%	1.355	1.497	0.814	0.836	1.228	1.248	1.148	1.323	1.791
	-2%	0.663	0.573	1.191	1.238	0.742	0.775	0.748	0.754	0.554
	4%	1.669	1.972	0.671	0.891	1.375	1.432	1.278	1.571	2.192
	-4%	0.338	0.200	1.270	1.195	0.483	0.564	0.394	0.620	0.360
	6%	2.060	2.659	0.616	0.851	1.716	1.703	1.546	1.856	2.887
	-6%	0.132	0.037	1.277	1.061	0.318	0.416	0.194	0.587	0.282

Table B3-16: Road gradient factors for Euro II diesel and petrol vehicles (factor = 1 at 0% gradient).

	Gradient	Diesel vehicle					Petrol vehicle			
		FC	NO_x	HC	CO	PM	FC	NO_x	HC	CO
Urban	2%	1.245	1.352	0.945	0.987	1.235	1.190	1.125	1.312	1.354
	-2%	0.770	0.687	1.047	1.019	0.764	0.807	0.819	0.728	0.716
	4%	1.540	1.797	0.941	1.013	1.577	1.438	1.231	1.918	2.118
	-4%	0.572	0.444	1.125	1.066	0.575	0.637	0.623	0.564	0.524
	6%	1.909	2.403	0.979	1.568	2.003	1.722	1.414	2.798	3.423
	-6%	0.380	0.257	1.036	0.947	0.338	0.511	0.512	0.438	0.376
Rural	2%	1.311	1.430	0.890	1.011	1.313	1.229	1.236	1.445	1.488
	-2%	0.813	0.727	1.491	1.464	0.922	0.822	0.815	0.708	0.709
	4%	1.661	1.908	0.814	0.979	1.675	1.469	1.469	2.097	2.276
	-4%	0.570	0.442	1.573	1.493	0.649	0.601	0.536	0.463	0.431
	6%	2.070	2.460	0.995	1.030	2.154	1.702	1.654	2.663	2.920
	-6%	0.316	0.209	1.326	1.141	0.283	0.448	0.397	0.299	0.258
	8%	2.443	2.904	1.147	1.265	2.503	2.110	2.537	2.988	3.396
	-8%	0.169	0.082	1.505	1.251	0.127	0.337	0.311	0.189	0.138
	10%	2.911	3.340	1.740	1.929	2.938	2.471	2.699	2.532	2.461
	-10%	0.106	0.044	1.408	1.119	0.067	0.272	0.256	0.152	0.092
Motorway	2%	1.356	1.489	0.745	0.666	1.331	1.271	1.735	1.786	2.048
	-2%	0.661	0.581	1.253	1.381	0.643	0.732	0.540	0.537	0.493
	4%	1.672	1.954	0.524	0.519	1.579	1.474	1.701	2.593	3.022
	-4%	0.335	0.213	1.406	1.488	0.276	0.461	0.361	0.244	0.220
	6%	2.065	2.632	0.432	0.451	2.006	1.665	1.972	3.882	4.465
	-6%	0.129	0.044	1.474	1.453	0.081	0.265	0.227	0.130	0.120

Table B3-17: Road gradient factors for Euro III diesel and petrol vehicles (factor = 1 at 0% gradient).

	Gradient	Diesel vehicle					Petrol vehicle			
		FC	NO_x	HC	CO	PM	FC	NO_x	HC	CO
Urban	2%	1.197	1.404	1.075	1.650	1.207	1.190	1.125	1.312	1.354
	-2%	0.827	0.673	0.905	0.655	0.855	0.807	0.819	0.728	0.716
	4%	1.440	1.954	1.192	2.226	1.426	1.438	1.231	1.918	2.118
	-4%	0.686	0.411	0.794	0.504	0.772	0.637	0.623	0.564	0.524
	6%	1.715	2.686	1.315	2.642	1.564	1.722	1.414	2.798	3.423
	-6%	0.544	0.253	0.591	0.424	0.635	0.511	0.512	0.438	0.376
Rural	2%	1.271	1.481	1.114	1.622	1.503	1.229	1.236	1.445	1.488
	-2%	0.766	0.642	0.880	0.560	0.681	0.822	0.815	0.708	0.709
	4%	1.573	2.030	1.235	1.873	1.892	1.469	1.469	2.097	2.276
	-4%	0.587	0.387	0.721	0.332	0.489	0.601	0.536	0.463	0.431
	6%	1.915	2.468	1.515	1.552	2.102	1.702	1.654	2.663	2.920
	-6%	0.471	0.207	0.570	0.210	0.392	0.448	0.397	0.299	0.258
	8%	2.244	2.855	1.784	1.862	2.586	2.110	2.537	2.988	3.396
	-8%	0.383	0.074	0.471	0.139	0.369	0.337	0.311	0.189	0.138
	10%	2.691	3.274	2.390	2.501	3.550	2.471	2.699	2.532	2.461
	-10%	0.313	0.040	0.383	0.104	0.438	0.272	0.256	0.152	0.092
Motorway	2%	1.315	1.715	1.124	3.223	1.287	1.271	1.735	1.786	2.048
	-2%	0.706	0.527	0.922	0.104	0.762	0.732	0.540	0.537	0.493
	4%	1.602	2.428	1.232	5.862	1.548	1.474	1.701	2.593	3.022
	-4%	0.434	0.192	0.736	0.040	0.554	0.461	0.361	0.244	0.220
	6%	1.919	3.335	1.458	6.940	1.905	1.665	1.972	3.882	4.465
	-6%	0.277	0.045	0.381	0.013	0.429	0.265	0.227	0.130	0.120

Table B3-18: Road gradient factors for Euro IV diesel and petrol vehicles (factor = 1 at 0% gradient).

	Gradient	Diesel vehicle					Petrol vehicle			
		FC	NO_x	HC	CO	PM	FC	NO_x	HC	CO
Urban	2%	1.197	1.404	1.075	1.650	1.207	1.180	1.127	1.100	1.296
	-2%	0.827	0.673	0.905	0.655	0.855	0.831	0.842	0.930	0.781
	4%	1.440	1.954	1.192	2.226	1.426	1.400	1.120	1.207	1.820
	-4%	0.686	0.411	0.794	0.504	0.772	0.662	0.662	0.896	0.614
	6%	1.715	2.686	1.315	2.642	1.564	1.659	1.203	1.396	2.693
	-6%	0.544	0.253	0.591	0.424	0.635	0.537	0.535	0.893	0.411
Rural	2%	1.271	1.481	1.114	1.622	1.503	1.229	1.061	1.214	1.278
	-2%	0.766	0.642	0.880	0.560	0.681	0.804	0.852	0.826	0.837
	4%	1.573	2.030	1.235	1.873	1.892	1.474	1.116	1.484	1.553
	-4%	0.587	0.387	0.721	0.332	0.489	0.624	0.699	0.687	0.665
	6%	1.915	2.468	1.515	1.552	2.102	1.709	1.281	1.698	1.659
	-6%	0.471	0.207	0.570	0.210	0.392	0.486	0.579	0.593	0.502
	8%	2.244	2.855	1.784	1.862	2.586	2.035	1.362	2.060	2.692
	-8%	0.383	0.074	0.471	0.139	0.369	0.384	0.482	0.648	0.294
	10%	2.691	3.274	2.390	2.501	3.550	2.399	2.100	2.190	2.935
	-10%	0.313	0.040	0.383	0.104	0.438	0.312	0.413	0.678	0.178
Motorway	2%	1.315	1.715	1.124	3.223	1.287	1.281	0.922	1.415	1.235
	-2%	0.706	0.527	0.922	0.104	0.762	0.740	0.989	0.737	0.722
	4%	1.602	2.428	1.232	5.862	1.548	1.530	1.030	1.902	1.364
	-4%	0.434	0.192	0.736	0.040	0.554	0.483	0.898	0.543	0.435
	6%	1.919	3.335	1.458	6.940	1.905	1.923	1.006	2.763	1.785
	-6%	0.277	0.045	0.381	0.013	0.429	0.299	0.584	0.376	0.325

Vehicle load

From the measurements at different loads, the final factors for diesel cars (FC, NO_x and PM) and petrol cars (FC) were calculated by linear interpolation. These final factors were representative for an average loading situation in Europe, with approximately 1.5 persons per vehicle (**Table B3-19**).

Table B3-19: Loading factors for diesel and petrol vehicles for different traffic situations.

Vehicle type	Traffic situation	FC	NO_x	PM
Diesel	Urban	1.014	1.112	0.951
	Rural	1.006	1.086	0.886
	Motorway	0.993	1.016	1.011
Petrol	Urban	1.026		
	Rural	1.010		
	Motorway	1.039		

Conclusions

Road gradient

Because of the different vehicles tested in ARTEMIS (engine capacity, power, *etc.*), from every single measurement a factor was calculated to represent the ratio between the measured emissions at *x*% road gradient and the measured emissions at 0% road gradient. Using this single factor, average factors for all road gradients were generated separately for petrol and diesel vehicles. As only Euro III vehicles were tested, and only over one driving cycle which represented a rural traffic situation, it was not possible to create factors for other traffic situations and different Euro categories from the measurements. Therefore, the missing factors were calculated using PHEM.

Before the application of the emission model, comparisons between the predictions and the measurement were made. For these comparisons, as well as for the subsequent simulations, the driving cycles had to be defined. For urban driving a Handbook cycle was used. For rural driving the ARTEMIS rural cycle (adjusted for higher road gradients) was used, and for the motorway situation a cycle recorded on a hilly motorway in Austria was chosen. Using these three cycles and average engine maps, the road gradient factors for all petrol and diesel Euro categories were calculated.

Vehicle load

Measurements were made for three different vehicle load levels and over four different driving cycles. The cycles covered the three main traffic situations: urban, rural and motorway. The load levels with no payload and with the maximum vehicle payload were measured, as well as one 'half-loaded' setting. The simulation of the vehicle load effect was quite sensible for vehicle payload of 100 kg, and therefore the loading factors were generated from the measurements. The final factors represented an average loading situation in Europe (1.5 persons per vehicle), but only factors for NO_x and PM for diesel cars, and fuel consumption for both diesel and petrol cars, were calculated. For the other exhaust gas components, the measured load factors were within the range of the repeatability during the emission tests.

B3.3.2 Unregulated pollutants

As well as the pollutants regulated by emission standards (CO, HC, NO_x, and PM for diesel cars), road vehicle exhaust contains many other compounds that may be of environmental significance. In relation to air quality, the pollutants that are currently causing most concern are NO_2 and particles (currently regulated in air quality standards as PM_{10}). In addition, whilst large numbers of hydrocarbon species are present in vehicle exhaust, vehicle emission regulations only consider total hydrocarbons, and air quality standards exist for only two species: benzene and 1,3-butadiene.

Pollutants considered

Volatile organic compounds (VOCs)

Total emissions of VOCs are controlled at vehicle type approval by legislative standards, although, as indicated above, individual compounds are not determined at present. Some of these individual compounds are potentially harmful to health, especially PAHs. VOCs are also involved in the formation of ground-level ozone and other oxidants, and the different VOC species contribute very differently to oxidant formation. Clearly, more information about the range and concentrations of hydrocarbon species is required to better inform the direction of future regulation.

The 1990 amendment of the US Clean Air Act defined some air pollutants as 'toxic', of which PAHs and four VOCs (benzene, 1,3-butadiene, formaldehyde and acetaldehyde) are emitted by road vehicles. These four VOCs have very different impacts on health. From measurements on 25 passenger cars, Flandrin *et al.* (2002) showed that in dense urban areas the most important compounds in relation to lung cancer are 1,3-butadiene, then benzene, formaldehyde and finally acetaldehyde. More generally, the USEPA (2000) has identified nine VOCs as 'mobile air toxics', and Flandrin *et al*. (2002) give a list of 12 VOCs emitted by transport to be considered as toxic (**Table B3-20)**. Naphthalene belongs to the second list, but was already included in the group of the four most volatile PAHs. Recently, a working group of the French Ministry of Health selected the hazardous compounds to be taken into account for the health risk assessment of road infrastructure, after considering a long list of atmospheric pollutants (Cassadou *et al*., 2004). By combining toxicological values and emission factors, the working group calculated a score for each compound (emission factor x reference toxicological value). The 16 compounds with the highest score were selected, of which six were VOCs (**Table B3-20)**.

In addition, the French working group recommended that emissions of the following compounds (level 2 in **Table B3.20**) should also be considered:

- Monobromomethane, 1,2 dibromoethane, and manganese, because of the proximity of the reference toxicological values and ambient concentrations and/or the high health hazard.
- Acetone, which is emitted by $DeNO_x$ systems.
- Ethylbenzene, *n*-hexane, naphtalene (PAH), styrene, toluene, xylenes, for which the emission factors are low but the reference toxicological values are high.
- 1,2,3,7,8,9-hexachlorodibenzodioxine and 2,3,7,8-tetracholodibenzo-para-dioxine, again because of high reference toxicological values.

The second application of VOC speciation is in the modelling of photochemical pollution. The different VOC species contribute very differently to the formation of ozone and other oxidants, according to their Maximum Incremental Reactivity (MIR) (Carter, 2000). The ozone-forming potential of any emitted molecule, the so-called OFP, is defined by $OFP = \Sigma$ (MIR x EF), according to the emission factors EF. This scale, often used to assess the ozone formation potential of traffic, is developed for low VOC/NO_x ratios, when the ozone formation is more sensitive to VOC concentrations. As each organic compound has a specific MIR, it is justifiable to define VOC emission factors per compound. It should be noted that, at the moment, the Carter proposal is based on specific photochemical mechanisms and on US input data from South California. Consequently, this choice is clearly subject to evolution and progress in this field.

Table B3-20: List of VOC considered as toxic in relation to human health. Compounds with the highest scores (level 1 – Cassadou *et al*., 2004), and additional compounds to consider (level 2). Pollutants in bold correspond to the emission factors proposed in this Section (five 1st level VOCs (BaP excluded), 8 VOCs (BaP excluded)).

Compound	USEPA (2000)	Flandrin *et al*. (2002)	Cassadou *et al.* (2004)		Toxicity (IARC classification)
			Level 1	Level 2	
acetaldehyde	**X**	**X**	**XX**		**possibly carcinogenic (2B)**
acetone		X		X	
acrolein	**X**		**XX**		
benzene	**X**	**X**	**XX**		**carcinogenic (1)**
benzo[a]pyrene (PAH)	**X**		**XX**		
bromomethane				X	
1,3-butadiene	**X**	**X**	**XX**		**probably carcinogenic (2A)**
cumene		X			
1,2 dibromoethane				X	
ethylbenzene	**X**	**X**		**X**	**possibly carcinogenic (2B)**
formaldehyde	**X**	**X**	**XX**		**probably carcinogenic (2A)**
1,2,3,7,8,9 hexachlorodibenzodioxine				X	carcinogenic
n-hexane	**X**	**X**		**X**	**peripheric nervous system**
naphtalene (PAH)		X		X	
styrene		X		X	bone medulla, liver, possibly carcinogenic (2B)
2,3,7,8 tetracholodibenzo-para-dioxine				X	teratogene
toluene	**X**	**X**		**X**	**teratogene (3)**
xylenes	X	X		X	not classifiable as to its carcinogenicity (3)

When the OFP per VOC was calculated for different vehicle types and for motorway driving, it could be concluded that alkenes (olefins) and monoaromatic compounds were fully necessary to be measured, for diesel as for petrol cars. In addition, aldehydes and ketones (carbonyl compounds) should not be omitted for the diesel cars (with or without oxidation catalyst) as they appear to be rather important. The family of volatile organic compounds groups a vast array of molecules, which are classically classified as shown in **Table B3.22**.

Early photochemical pollution models of used only groups of VOCs. Newer models use the species themselves, differentiating between the species within each group, and with different MIRs. Therefore, emission factors need to be expressed per compound and, if possible, per group. The advantage of expressing the emission factors per group is the possibility of extrapolating emissions more easily.

ARTEMIS produced data on a huge number of different unregulated compounds, and especially VOCs (Aakko *et al*., 2005; 2006). The list of individual compounds analysed, however, varied by laboratory. Many individual compounds, such as benzene and formaldehyde, were analysed extensively at all five laboratories participating in the programme. It was necessary to select the species which could be regarded as the most important, most informative and most representative. These VOCs are listed **Table B3.20**: they are the six 'first level' VOCs and four of the 'second level' VOCs.

PAHs

The analysis of 16 PAHs is recommended by the US Environment Protection Agency according to their carcinogenic and mutagenic power. **Table B3-21** list compounds and their classification by the International Association for Research on Cancer (IARC, 1983; 1987), according to their toxicity. The group, defined here, of the six most carcinogenic PAHs contains all the PAHs classified in 1987 by IARC as probable (group 2A) or possible (group 2B) carcinogens. It should be noted that the IARC classification has changed recently (IARC, 2002; 2006) - we now have one PAH (BaP) classified as '1', one PAH classified as '2A' and seven PAHs classified as '2B'. Three more PAHs (BjF, Chr, N) should also now be added to the group of the most carcinogenic PAHs. In addition, the group of the four most volatile PAHs with the lightest molecular weight (N, Ace, Flu, Acy) are difficult to analyse as losses are significant. Therefore, the accuracy of the emission factors for these compounds is low, and most authors do not give any results. The 12 other PAHs should therefore be considered as the group of the 12 least volatile PAHs, including the group of the six most carcinogenic PAHs. Benzo[a]pyrene (BaP) belongs to both the 12 least volatile and the six most carcinogenic PAHs. It is the PAH which is reported the most often because it is very easy to measure, and therefore the best known. It is also the only PAH which is now classified as carcinogenic (class 1). Therefore, specific emission factors should be provided for BaP.

A recent European Directive (2004/107/EC of 15 December 2004) requires Member States to monitor at least seven relevant PAHs at a limited number of sites (see **Table B3-21**), *i.e*. the 6 most carcinogenic PAHs and the BjF. BghiP is also an indicator of the petrol emissions, with indenopyrene (IP). In addition, a distinction can be made between gas-phase and particle-phase PAHs. Both phases are present in the three groups, with ratios of between 20% and 80 % for Euro II vehicles (Joumard *et al*., 2004a; 2004b). The different groups of PAHs are given in **Table B3-21**.

Table B3-21: PAHs proposed by USEPA and European directive 2004/107. IARC classification: 1 = carcinogenic, 2A = probably carcinogenic, 2B = possibly carcinogenic, 3 = not classifiable as to carcinogenicity, 4 = probably non-carcinogenic. Pollutants in bold correspond to the emission factors proposed in this Section.

Full name	Short name	IARC classification		USEPA	2004/107/EC	4 most volatile	12 least volatile	**6 most carcinogenic**
		1983; 1987	2002; 2006					
acenaphthene	Ace	-	-	X		Ace		
acenaphthylene	Acy	-	-	X		Acy		
anthracene	An	3	3	X			An	
benzo[a]anthracene	BaA	2A	2B	X	X		BaA	BaA
benzo[a]pyrene	**BaP**	**2A**	**1**	**X**	**X**		**BaP**	**BaP**
benzo[b]fluoranthene	BbF	2B	2B	X	X		BbF	BbF
benzo[g,h,i]perylene	BghiP	3	3	X			BghiP	
benzo[j]fluoranthene	BjF	-	2B		X			
benzo[k]fluoranthene	BkF	2B	2B	X	X		BkF	BkF
chrysene	Chr	3	2B	X			Chr	
dibenzo[a,h]anthracene	DBahA	2A	2A	X	X		DBahA	DBahA
fluoranthene	F	3	3	X			F	
fluorene	Flu	3	3	X		Flu		
indeno[1,2,3-c,d]pyrene	IP	2B	2B	X	X		IP	IP
naphthalene	N	-	2B	X		N		
phenanthrene	Phe	3	3	X			Phe	
pyrene	P	3	3	X			P	

As for VOCs, the PAH ARTEMIS database is an inharmonic set of data, with large differences between laboratories. Therefore only the benzo[a]pyrene and the sum of the 6 most carcinogenic PAHs are considered (see **Table B3.21**) when providing emission factors.

Primary NO_2

Most of the NO_x in vehicle exhaust is usually present as NO, whereas most of the NO_2 in the atmosphere is formed by the reaction of NO with ozone (O_3). In ambient roadside air, NO_2 levels are generally limited by the local concentration of O_3 rather than the emission of NO from vehicles. The NO_2 which *is* emitted directly from vehicle exhaust is commonly referred to as 'primary NO_2'. Even though NO_2 is an important pollutant there is surprisingly little information on primary emissions. It is generally assumed for air quality modelling purposes that the proportion of NO_x in vehicle exhaust which is emitted as NO_2 is 5% (volume fraction). The figure of 5% was based on relatively old measurements, from vehicles without after-treatment system. However, laboratory work, remote sensing studies, tunnel studies and ambient air pollution measurements have indicated that the actual proportion varies according to factors such as vehicle type, operating condition, and the measurement method, and can be much higher than 5%, especially for diesel vehicles (Latham *et al*., 2001; Jimenez *et al.*, 2000; Kurtenbach *et al*., 2001; Jenkin, 2004; Carslaw and Beevers, 2004; Carslaw, 2005). It has also been suggested that recent increases in the NO_2 proportion in NO_x from diesel vehicles are linked to exhaust after-treatment devices, such as oxidation catalysts and continuously regenerating traps (CRTs) (*e.g.* Carslaw and Beevers, 2004).

Particulate matter

Current vehicle type-approval legislation requires the filter-based measurement of total mass of particulate matter (*i.e.* g/kWh for heavy-duty engines and g/km for light-duty vehicles) and applies only to vehicles powered by diesel engines[12]. However, there are a number of reasons why alternatives to a standard based on total mass alone are desired, and why the emphasis may change from particle mass to other metrics relating to particle size, number and surface area. For example, the mass concentration of particles in the exhaust of diesel engines has reduced steadily over the last 20 years following the development and application of new technologies. Current and future legislation is reducing particulate mass emissions, and diesel targets, towards the threshold of reliable measurement. Standards based solely on total particulate mass are not ideal in terms of minimising the risks to health, as the size of particles determines how deeply they penetrate into the human respiratory system and where they are deposited. Conventional filter methods for assessing total exhaust particulate matter do not provide meaningful information on the ultrafine particles (smaller than 0.1 µm), which contribute little to the total mass.

Particle emissions should consequently be expressed according to different metrics (Samaras *et al.*, 2005b), as the integrated active surface of the total particle population, the total particle number, the particle size distribution, the number of solid particles in different size ranges (aerodynamic diameter of 7-50 nm, 50-100 nm and 100 nm - 1 µm for instance).

Pollutants covered and analytical techniques used

The regulated pollutants and CO_2 were measured systematically during all the ARTEMIS tests. In addition, a large number of unregulated pollutants - especially hydrocarbon species - were measured by five laboratories (Aakko *et al.*, 2005, 2006). The compounds quantified and characterised are given per laboratory and per pollutant group in **Table B3-22,** and in detail in (Joumard *et al.*, 2007). In total, 169 unregulated pollutants were measured. 74 passenger cars were tested by EMPA, IM, INRETS, KTI and VTT, with 5 to 25 driving cycles per car, including both cold-start and hot-start cycles (Joumard *et al.*, 2007) (**Table B3-23**).

Table B3-22: Numbers of unregulated pollutants measured per laboratory and per type.
The groups of VOCs with the highest ozone forming potential are marked in italics.

Unregulated pollutant group	EMPA	IM	INRETS + ULCO	INRETS + US	INRETS + USTL	KTI	VTT	Total
Non-VOCs			1			1		2
Alkanes (saturated)	35	15	41			1	3	50
Alkenes and alkynes (unsaturated)	*24*	*3*	*19*				*5*	*28*
Monoaromatic hydrocarbons	*25*	*2*	*32*			*4*	*5*	*39*
Polyaromatic hydrocarbons (light)	1	6	3	6		1		8
Polyaromatic hydrocarbons (heavy)		20		10		1		22
Carbonyl compounds (aldehydes and ketones)	*13*	*12*			*16*	*1*		*20*
Total	98	58	96	16	16	9	13	169

[12] PM limits are currently proposed for Euro V and Euro VI vehicles with direct-injection petrol engines.

Table B3-23: Test scheme for the unregulated pollutant measurements.

Laboratory	No. veh.	Components analysed	No. driving cycles	Main driving cycles
EMPA	18	7	39	NEDC, 3 ARTEMIS, INRETS urbain fluide court, INRETS route court, EMPA BAB 1000, Handbook R1, R2, R3 & R4, FTP 75
		190 HCs	18	3 ARTEMIS, INRETS urbain fluide court
IM	11	VOC & PAH	11	NEDC, 3 ARTEMIS, INRETS urbain fluide court, INRETS route court
INRETS-US-ULCO-USTL	30	VOC & PAH	4	INRETS urbain fluide court, VP fa/fo mot. urbain & autoroute
KTI	2	VOC & PAH	8	NEDC, INRETS urbain fluide court, INRETS route court
VTT	6	VOC	7	NEDC, 2 ARTEMIS, INRETS urbain fluide court by gas chromatography
	13		7	As above, by FTIR

The sampling procedures and methods of analysis for unregulated pollutants were dependent upon on the laboratory and the pollutant group. On-line measurements were performed by EMPA using chemical ionisation mass spectrometry (CI-MS) for methane, benzene, toluene, xylenes and ethylbenzene, and by VTT using Fourier-transform infrared (FTIR) for N_2O, NO/NO_2, NH_3 and formaldehyde. All other measurements were conducted off-line, and different methods were used:

- Gas chromatography with flame ionisation detection (GC-FID) for about 110 VOC species by EMPA (Heeb *et al.*, 2002, 2004; Saxer *et al.*, 2002, 2003; Weilenmann *et al.*, 2003b, 2005), for 18 species by IM (Prati *et al.*, 2003a, 2003b, 2005), and for C_2-C_6 compounds by INRETS-ULCO (Caplain *et al.*, 2004, 2006; Joumard *et al.*, 2004a, 2004b).
- Gas chromatography with mass spectrometry (GC-MS) for PAHs by IM and KTI, and for C_6-C_{15} compounds by INRETS-ULCO (references as above).
- Gas chromatography for 13 compounds up to C_8 by VTT.
- High-performance liquid chromatography (HPLC) for aldehydes and ketones by EMPA, IM, INRETS-USTL, KTI and VTT, and for PAHs by INRETS-US (Paturel *et al.*, 2003, 2005; Devos *et al.*, 2006; Joumard *et al.*, 2004a, 2004b).

In the PARTICULATES project (Samaras *et al.*, 2005b), a dedicated sampling and measurement system was used in several laboratories to characterise particle emissions from light-duty vehicles. The results from these measurements were used to develop emission factors for several particle properties other than filter-based mass. In particular, emission factors were developed for particle number (size range >7 nm) and the integrated active surface area (7 nm - 1 µm) of the total particle population (referred to hereafter as the 'active surface area'), as well as the number of solid particles in three different ranges: 7-50 nm, 50-100 nm and 100 nm-1 µm (aerodynamic diameter). Only transient hot-start driving cycles were considered in the development of these emission factors. Separate emission factors were developed for urban, rural and motorway conditions using the results obtained under the corresponding ARTEMIS cycles.

Based on a preliminary study, the only significant fuel effect observed was that of sulphur content on the total particle number and active surface area of diesel PM. Therefore, separate emission factors were derived for diesel fuels fulfilling two different specifications, <350 ppm wt. S and <50 ppm wt. S. On the other hand, a single emission factor, independent of the fuel used, was produced for petrol vehicles. **Table B3-24** shows the vehicle categories tested and the sample sizes. Due to the relatively small vehicle sample no further categorisation was applied with respect to engine capacity.

Table B3-24: Car categories considered and numbers of vehicles tested.

Car category	Number of vehicles tested
Diesel Euro I	1 simulated*
Diesel Euro II	2
Diesel Euro III	4
Diesel Euro III, DPF	4 OEM + 1 retrofitted with 2 particle traps
Petrol Euro I	1
Petrol Euro III	4
Petrol Euro III, DISI	3 in lean mode + 2 in stoichiometric mode

*The particular vehicle was a Euro II diesel which was tested with its oxidation catalyst removed in an attempt to simulate Euro I levels.

Experimental results and emission factors

From the large amount of emission measurements carried out for unregulated pollutants within ARTEMIS, new emission factors were derived for some VOCs and PAHs. In addition, by taking into account the outputs of the PARTICULATES project and other campaigns, new emission factors for NO_2 and particles properties were derived.

Primary NO_2

Since the early 1970s, NO_X exhaust emissions have generally declined, and the proportion of primary NO_2 in vehicle exhaust has been estimated to be between 0% and 10% by volume. A value of 5% has been widely accepted and applied to emission inventories and dispersion modelling approaches incorporating first principal chemistry schemes (AQEG, 2006). This 5% value was derived from relatively few tests on vehicles without complex exhaust after-treatment systems, and it is questionable if it was ever robust, or indeed if it is applicable to modern vehicles (Campau and Neerman, 1966).

The proportion of primary NO_2 in vehicle exhaust has been investigated during the last 10 years (Latham *et. al.* 2001), but robust evidence has remained limited and uncertain. However, it is evident that primary NO_2 emissions are higher from diesel vehicles, the proportion of which has grown in many national fleets across the EU. In addition, primary-NO_2 has been shown to be higher from various exhaust after-treatment technologies, entering the market after 1992. Furthermore, the introduction of leaner burn petrol engine technologies such as the gasoline direct injection (GDI), are associated with increased NO_X formation. All of the evidence, therefore, suggests that the 5% primary NO_2 factor is a significant underestimation.

Gense *et al.* (2006) and AQEG (2006) presented state-of-the-art reviews of the origins, measurement and impacts of primary NO_2 emissions in relation to modern road vehicles and specific emission-control technologies. Data on primary NO_2 emissions, and the proportion of NO_2 in NO_x, were gathered from measurement programmes carried out by Ricardo (2003), Millbrook (2005), TRL (2001), LAT, TNO Automotive and EMPA. These data were reviewed with respect to their accuracy and reliability

These data showed that the measurement method has a substantial influence on the measured primary NO_2 emissions, and the balance between NO and NO_2 was found to be very sensitive to the measurement conditions. The defined measurement procedure involves the determination of the NO_2 mass emission by means of simultaneous analysis of the NO and NO_x concentrations in the raw (undiluted) exhaust gas, sampled on-line at the exhaust pipe. For the gas analysis an instrument using the chemiluminescence principle was proposed. However, problems relating to interference from ammonia will need to be considered when testing near-future SCR-DeNO$_x$ systems (and also petrol-engined vehicles which are known to emit substantial amounts of ammonia). The test procedure was used as the basis for a large-scale measurement programme at TNO Automotive and EMPA, in which a total of 63 petrol and diesel cars were tested, from pre-Euro I to Euro IV. Some other vehicles were tested by Ricardo, Millbrook and LAT.

The results from the measurement programme showed some clear trends (see **Figure B3-11**). The measured levels of NO_2 and the fraction of NO_2 in NO_x were higher for diesel cars than for petrol cars. For diesel cars the fraction ranged from about 5% to almost 80 %. A large step change was evident for diesel cars from Euro II to Euro III. From pre-Euro I to Euro II the average NO_2 fraction did not vary much, and was about 15-20% (an average of 17% was assumed). For Euro III diesel cars the measured NO_2 fraction was considerably higher, at around 50%. The absolute NO_2 emission increased sharply from Euro II to Euro III, and remained at the same level for Euro IV. Measurements on four cars (three with a catalysed diesel particle filter and one with a D-kat) yielded NO_2 proportions which were higher than 50%.

For petrol cars the measured absolute NO_2 emissions were low compared with those of modern diesel cars, as both the fraction of NO_2 and the absolute level of NO_x were much lower. As the values were too low to determine reliable estimates, Gense *et al*. (2006) considered that no accurate NO_2 fractions could be determined for petrol cars. However, it has been assumed here that typical average NO_2 fractions would be 3% and 9% for pre-Euro I and Euro III/IV petrol cars respectively. For petrol Euro I/II cars, an intermediate fraction of 6% has been assumed. The average speed seems to have a negative influence on the NO_2 fraction for pre-Euro I to Euro II vehicles (AQEG, 2006), but no influence for more recent Euro III and Euro IV vehicles (Ricardo, 2003; Millbrook, 2005). Therefore, average speed is not included as a predictive variable in the ARTEMIS emission factors. The NO_2 fractions for the different passenger car categories are given in **Table B3-25**.

Table B3-25: NO_2 as a percentage of NO_x for different car categories, based on the results presented by Gense *et al*. (2006) and AQEG (2006).

	Petrol			Diesel	
	Pre-Euro I	Euro I-II	Euro III-IV	Pre-Euro I to Euro II	Euro I I-IV
NO_2 fraction (%)	3	6	9	17	50

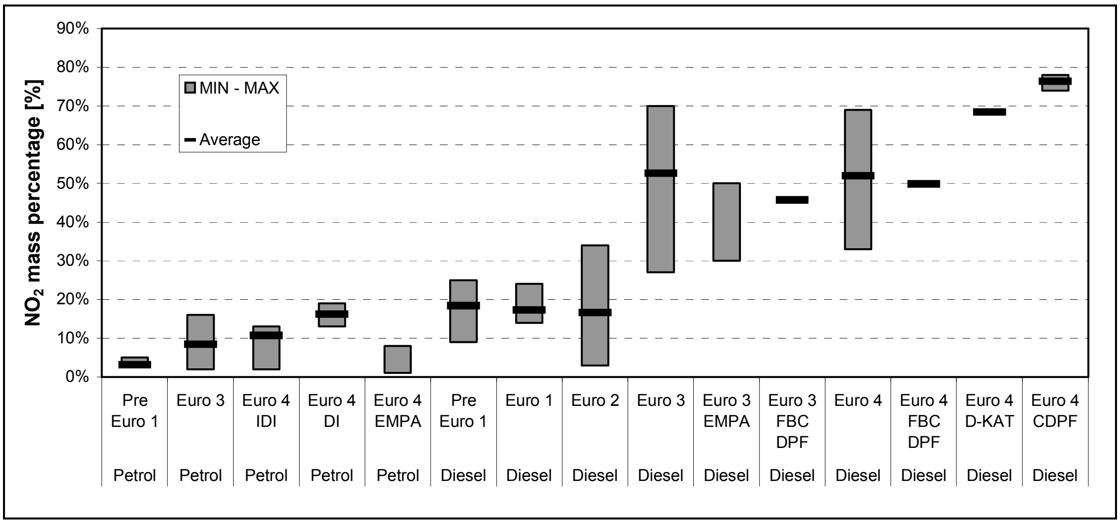

Figure B3-11: NO_2 percentage of NO_x for various fuels, technologies and emission standards, including the ranges (minimum and maximum values), as measured by TNO Automotive and EMPA (Gense *et al*., 2006).

Particle properties

The emission factors for total and solid particle populations are summarised in **Table B3-26** and **Table B3-27** respectively.

Table B3-26: Emission factors for active surface area and particle number of the total particle population.

Total particle population		Active surface area [m^2/km]			Total particle number [#/km] $\times 10^{-14}$		
Car category	Fuel specs (EN590)	Urban	Rural	Motorway	Urban	Rural	Motorway
Diesel Euro I	2000-2009	20.97	19.13	29.36	4.0	3.0	3.2
Diesel Euro II	2005-2009	16.82	17.05	27.77	2.1	2.0	4.3
	2000			36.19			7.1
Diesel Euro III	2005-2009	15.31	13.43	18.51	1.6	1.7	2.8
	2000			39.31			12.3
Diesel Euro III DPF	2005-2009	0.012	0.013	0.22	0.00067	0.09	1.8
	2000		4.03	44.62		1.7	13.4
Petrol Euro I	later than 2000	0.68	0.43	0.50	0.088	0.073	0.18
Petrol Euro III	later than 2000	0.024	0.033	0.074	0.007	0.053	0.056
Petrol Euro III DISI	later than 2000	2.04	1.77	2.48	0.15	0.11	0.90

Table B3-27: Emission factors for solid particle number in the size ranges 7-50 nm, 50-100 nm and 100-1 µm (aerodynamic diameter. Fuel specifications later or equal to EN590:2000.

Solid particle population [#/km] $\times 10^{-13}$	Number of solid particles <50 nm			Number of solid particles 50-100 nm			Number of solid particles 100-1000 nm		
Car category	Urban	Rural	M'way	Urban	Rural	M'way	Urban	Rural	M'way
Diesel Euro I	8.5	8.6	7.2	9.3	7.8	7.3	5.4	3.8	4.0
Diesel Euro II	7.6	7.6	6.1	8.8	7.7	7.2	5.1	3.6	4.0
Diesel Euro III	7.9	7.1	5.8	8.7	6.8	6.9	4.5	3.2	3.5
Diesel Euro III DPF	0.0055	0.0040	0.023	0.0023	0.0016	0.0094	0.0016	0.0012	0.0028
Petrol Euro I	0.32	0.24	0.086	0.14	0.10	0.034	0.052	0.037	0.012
Petrol Euro III	0.0096	0.011	0.0055	0.0044	0.0054	0.0028	0.0026	0.0034	0.0051
Petrol Euro III DISI	0.81	0.61	0.28	0.65	0.36	0.19	0.41	0.21	0.15

VOCs and PAHs

Aakko *et al.* (2005, 2006) noted that there were clearly some differences - sometimes several orders of magnitude - between the emission levels obtained at the different laboratories, and a number of inconsistencies in the data. For example, in some cases the emission factor for a single compound was higher than that for total hydrocarbons. The test matrices at the five laboratories were different. Different vehicles and driving cycles were used, and the compounds analysed varied. Consequently, the sum total emission factors for pollutant groups of groups (*e.g.* homologous series such as alkanes, alkenes) were not comparable between laboratories. The most problematic emission categories (in terms of the numbers of samples) were Euro IV petrol cars (two cars tested), pre-Euro I diesel cars (two cars tested) and Euro I diesel cars (three cars tested). The sample size in these emission categories was so low that that the final conclusions on emission factors should be viewed with caution.

The comparability between laboratories was studied by separating the results for cars in the same emission class. At EMPA, IM, KTI and VTT several common test cycles were used. For benzene, the EMPA, IM, KTI and VTT results appeared to be consistent (in the same range), but the INRETS results were an order of magnitude higher, especially (but not only) for petrol cars. For formaldehyde, INRETS data were also an order of magnitude higher than EMPA figures, with the IM results being intermediate. In the case of PAHs analysed by INRETS, IM and KTI, INRETS, the values for BaP were two or three orders of magnitude lower than the IM results, with the KTI results being intermediate. These results seem to be in accordance with the results from literature. However, the differences in the levels of PAH results obtained at IM and INRETS were significant, and had to be taken into account when the conclusions were drawn. The simple averages of emission factors may give misleading results when test matrices are not harmonised and emission levels vary from one laboratory to another. However, the evolution of the emission categories of cars can be monitored within a laboratory. Only the final emission factors for PAHs need careful consideration.

The comparability of the laboratories was fairly good in relation to benzene and formaldehyde emissions, even though the benzene level was somewhat higher at INRETS, and formaldehyde level lower at EMPA, than the respective emissions at the other laboratories. The most significant difference between laboratories was seen in the PAH results. This is especially important, due to the fact that the test matrix for PAHs was not as extensive as, for example, the matrices for benzene or formaldehyde. Thus, the PAH results had to be carefully considered when the conclusions were drawn, and the emission factors given below should be taken with caution. Further work is required in this area.

Taking into account the limitations of the results described above, average emission factors were calculated for the unregulated compounds listed in **Table B3-28** (overleaf) (Aakko *et al.*, 2005, 2006).

The VOC emission factors decreased dramatically from pre-Euro I to Euro I petrol cars (on average, by an order of magnitude – See **Figure B3-12**). The decrease was lower, by a factor of 5 to 10 from Euro I to Euro III. This evolution depended on the species. For diesel cars, the decrease also occurred, but was much lower: by 50% only from pre-Euro I to Euro I, and from Euro I to Euro II.

PAH emissions from petrol cars also decreased by a order of magnitude from pre-Euro I to Euro I and then only by 40% from Euro I to Euro III. Emissions of benzo(a)pyrene increased by a factor of 3 between Euro I and Euro II/III.

The results from ARTEMIS are generally in line with those in the literature.

The separate measurement of particulate and semi-volatile phases showed that for petrol cars 35% and for diesel cars 23% of the six most carcinogenic PAHs were found in semi-volatile (gaseous) phase and the rest in particulate matter in the hot-start tests (Joumard *et al.*, 2004a; 2004b).

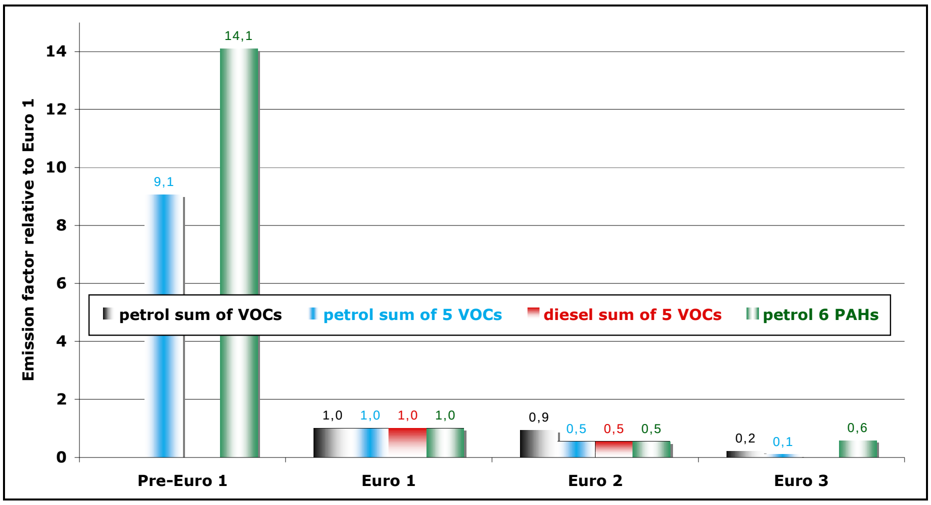

Figure B3-12: Influence of the emission standard on the emission factors of the sum of the eight VOCs considered, the five 1st level VOCs, all BaP excluded, and the sum of the six most carcinogenic PAHs (see **Table B3-20** and **Table B3-21** for the definitions of these compounds).

Table B3-28: Hot emission factors for unregulated VOCs and PAHs.

Pollutant		Petrol			Diesel		
	EU emission standard	Average (mg/km)	SD (mg/km)	Number of tests	Average (mg/km)	SD (mg/km)	Number of tests
Benzene	pre-Euro I	47.5	58.9	147	*8.7*	*0.0*	*1*
	Euro I	16.0	18.5	14	*5.3*	*9.0*	*8*
	Euro II	7.8	10.0	55	1.4	2.1	174
	Euro III	1.4	3.3	190	3.3	5.3	10
	Euro IV	0.3	0.7	10	na	na	na
1.3-butadiene	Pre-Euro I	*69.3*	*37.4*	*8*	na	na	na
	Euro I	0.38	0.53	10	*0.21*	*0.13*	*4*
	Euro II	0.00	0.00	29	0.00	0.00	8
	Euro III	0.03	0.10	61	0.00	0.00	7
	Euro IV	0.0	0.0	10	na	na	na
Ethylbenzene	pre-Euro I	na	na	na	*11.2*	*6.9*	*5*
	Euro I	*4.0*	*4.5*	*8*	*0.9*	*1.3*	*10*
	Euro II	12.1	23.6	36	6.3	8.7	38
	Euro III	4.4	13.1	34	*22.6*	*15.3*	*3*
	Euro IV	0.0	0.0	10	na	na	na
Toluene	pre-Euro I	208.1	204.4	147	*31.7*	*27.9*	*5*
	Euro I	15.6	12.5	14	*12.7*	*18.3*	*11*
	Euro II	16.0	32.9	60	3.0	10.0	187
	Euro III	2.5	9.8	191	*6.2*	*7.1*	*9*
	Euro IV	0.2	0.5	10	na	na	na
Hexane	pre-Euro I	*67.5*	*44.8*	*8*	*na*	*na*	*na*
	Euro I	3.7	3.6	10	*na*	*na*	*na*
	Euro II	1.0	1.1	25	*0.3*	*0.7*	*8*
	Euro III	0.1	0.3	49	*0.7*	*1.6*	*7*
Formaldehyde	pre-Euro I	32.0	14.4	18	*11.4*	*10.0*	*13*
	Euro I	0.8	1.0	31	*6.4*	*10.0*	*20*
	Euro II	1.0	1.4	51	4.8	6.8	52
	Euro III	0.4	0.5	65	3.6	4.1	20
Acetaldehyde	pre-Euro I	11.5	11.4	18	*7.7*	*6.1*	*13*
	Euro I	0.7	0.6	31	*6.6*	*8.3*	*20*
	Euro II	0.7	0.9	50	4.1	5.5	52
	Euro III	0.2	0.2	65	1.7	2.4	20
Acrolein	pre-Euro I	*2.6*	*0.1*	*3*	*1.5*	*2.0*	*12*
	Euro I	0.0	0.1	9	*0.8*	*1.2*	*6*
	Euro II	0.4	1.2	13	0.3	0.7	29
	Euro III	0.0	0.0	12	na	na	na
Sum of considered VOCs (from data above)	Pre-Euro I	438	371	na	*72*	*53*	*na*
	Euro I	41	41	127	*33*	*48*	*na*
	Euro II	39	71	319	20	35	548
	Euro III	8.9	27	667	38	36	na
	Euro IV	0.6	1.3	na	na	na	na
Benzo(a) pyrene	Pre-Euro I	0.025	0.027	8	*	*	*3*
	Euro I	0.002	0.003	11	*	*	*8*
	Euro II	0.007	0.002	39	0.000	0.001	53
	Euro III	0.007	0.001	47	0.001	0.001	24
Sum of the 6 most carcino-genic PAHs	Pre-Euro I	*0.112*	*0.104*	*8*	*	*	*3*
	Euro I	0.008	0.007	11	*	*	*8*
	Euro II	0.004	0.010	23	0.002	0.006	37
	Euro III	0.005	0.007	47	0.003	0.003	24
	Euro IV	na	na	na	na	na	na

* = average emission factor is not representative
Values in italics are based on samples, and the average emission factor may not be representative
na = no data available

B3.3.3 Cold-start emissions

Cold start emissions are treated separately in Part B7 of this Report.

B3.3.4 Effects of auxiliary systems

Research has indicated that the use of auxiliary systems, such as air conditioning (A/C) headlights, windscreen wipers and radios, can have a significant impact on emissions and fuel consumption. In fact, much of the work has focused on air conditioning (ECCP, 20003; Hugruel and Joumard, 2004; Barbusse *et al.*, 1998; Gense, 2000; Pelkmans *et al.*, 2002; Weilenmann *et al.*, 2004; Bernoulli *et al.*, 2003). For example, a European Climate Change Working Group estimated that the use of A/C systems under 'average' European conditions would cause an increase in fuel consumption of between 4% and 8% in 2020 (ECCP, 2003). However, a study carried out at INRETS Indicated an increase in fuel consumption of less than 1% for the year 2025 (Hugruel and Joumard, 2004). Other auxiliary systems have been studied in less detail.

In ARTEMIS, emissions data (CO_2, CO, HC, NO_x, and PM) relating to the effects of auxiliary systems (in particular, A/C) were collected. Parameters linked to technology and climatic conditions were investigated, and a new physical model was developed (Rujol, 2005; Roujol and Joumard, 2006). This work is summarised below.

Air conditioning*: *emission database and analysis of effects on fuel consumption and CO_2

The ARTEMIS emission factor database for A/C included experimental data from three laboratories (UTAC in France, CENERG in France and VITO in Belgium). It covered 27 vehicles and 146 tests. The vehicles had different propulsion systems (petrol, diesel) and engine sizes, and conformed with a range of emission standards (Euro I, Euro III and Euro IV). Most of the vehicles in the database had been approved to the Euro I standard. The driving cycles used, the number of vehicles tested, the types of vehicle tested and the experimental objectives varied according to the laboratory. The climatic conditions were also specific to each laboratory, and were chosen in order to represent severe climates.

In each test the definition adopted for the *excess emission* of a pollutant due to A/C was consistent, and was taken to be the difference between the emission with and without A/C with the vehicle running under the same conditions. Occasionally, this gave negative emissions due to A/C. A simple statistical analysis was undertaken to determine the most important parameters affecting emissions in relation to A/C. Prior to this analysis it was necessary to define the units for expressing the excess fuel consumption due to A/C (in volume per unit distance unit or per unit time). For physical reasons - *i.e.* there is no strong relationship between cooling demand and vehicle speed - volume per unit time (l/h) was selected. The excess emissions (CO_2 and regulated pollutants) due to A/C were then examined in terms of vehicle parameters, driving conditions and climatic conditions.

Effects of mean vehicle speed and driving cycle

Vehicle speed can influence the A/C system. For instance, the cooling of the condenser can be improved with speed, and the heat exchange coefficient depends on the air speed in the cabin of the car. However, mean vehicle speed was found to have little impact on excess fuel consumption. It seems that the main reason for this is the efficiency of the engine, which varies with load and engine speed. For the EUDC without A/C, the engine load and efficiency are low. For the same driving cycle with A/C running, the engine load is higher, and the engine efficiency is improved. The effect of A/C on fuel consumption is partially hidden by the improvement of engine efficiency. In the case of a constant high-speed cycle, the engine load is high and the variation of load due to A/C is low. With or without A/C running, the engine efficiency remains quite constant. In an experiment carried out at INRETS, two vehicles were studied under real driving conditions, and a similar conclusion was drawn from the results (Roumégoux *et al.*, 2004).

Effects of technological parameters

The relationships between fuel consumption and technological parameters were assessed for four vehicle categories, which were defined in terms of engine size, vehicle size, type of compressor and type of regulation (**Table B3-29**). Most of the test vehicles were equipped with a variable-displacement compressor. Only two small vehicles and one large vehicle were equipped with fixed-displacement compressors. All cars with an engine size of greater than 2.0 litres and SUVs were equipped with automatic temperature regulation systems. Apart from one vehicle, all small cars and medium-size cars with an engine size of less than 2.0 litres were equipped with manual temperature regulation systems. The average fuel consumption did not vary substantially be vehicle category, and that the standard deviation was quite large. It was therefore concluded that the effects of air conditioning on fuel consumption do not depend on technological parameters.

Table B3-29: Average fuel consumption due to A/C (l/h) for four vehicle types.

Vehicle category			Number of vehicle tests	Fuel consumption	
Vehicle size	Fuel	A/C type		Average	St. dev.
Small cars and medium-size cars (<2.0 l)	Petrol	Manual	38	0.7	0.2
	Diesel		55	0.68	0.22
Medium-size cars, large cars and SUVs (>2.0 l)	Petrol	Automatic	25	0.75	0.34
	Diesel		28	0.85	0.35

Effects of climatic conditions

Climatic conditions and ambient (outside) temperature are clearly going to have a large effect on A/C usage, and therefore on pollutant emissions. According to Barbusse *et al.* (1998), the solar load represents 45% of the total load on the A/C. The variation of excess fuel consumption with ambient temperature was lower than expected. The ambient temperature at which there was no cooling or heating, obtained by linear extrapolation, seemed to be below 0°C (**Figure B3-13**). Theoretically, the relationship between fuel consumption and ambient temperature is linear because convective heat gains are linearly linked to the difference between the outside and inside temperatures. That seems to demonstrate that A/C is running quite close to full load for outside temperature higher than 28°C. An extrapolation of these data is therefore not applicable. As the experiments did not include temperatures below 28°C and measurements of solar heat radiation, a physical model was developed.

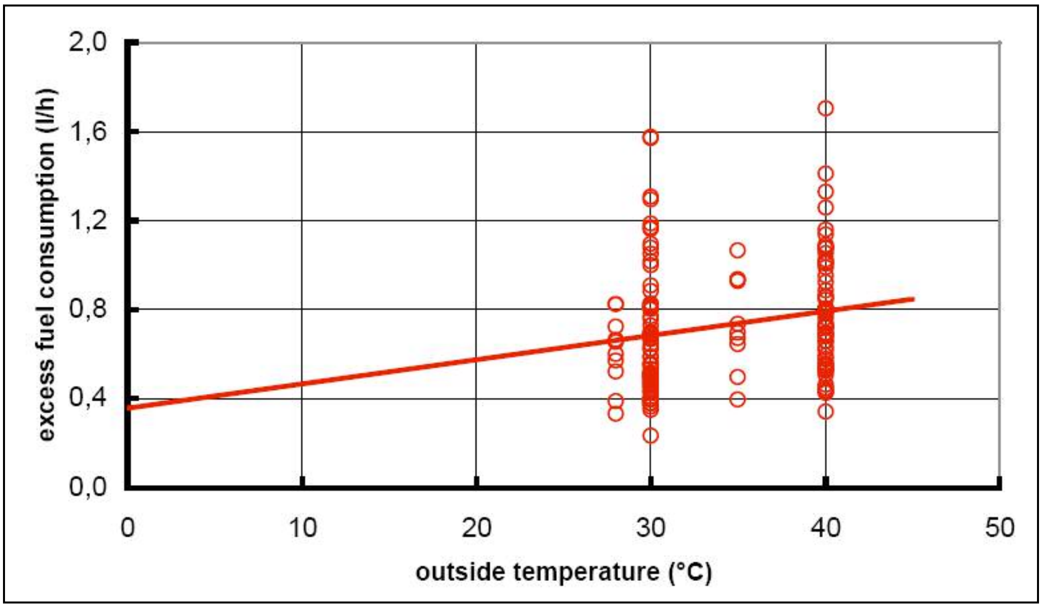

Figure B3-13: Excess fuel consumption (l/h) due to A/C versus ambient temperature (°C), with linear regression.

A physical model for air conditioning effects

The physical modelling approach needed to take into account each component involved in the vehicle system, including the cabin, the A/C system and the engine. The phenomena taken into account were heat exchanges between the cabin air and the outdoor air, heat exchanges between the evaporator and the A/C system - which allows a reduction in air flow temperature and leads to its dehumidification - and heat exchange between the A/C system and the engine.

Passenger compartment

The modelling of the passenger compartment was based on a description of heat exchange in buildings (Bolher *et al*., 2000). Air temperature and humidity in the cabin were assumed to be uniform, and the heat exchanges governing the temperature of cabin were assumed to be functions of the global heat exchange coefficient, UA (W.m^{-2}.K^{-1}), the untreated air flow rate due to permeability, m_p (kg.s^{-1}), the internal heat gains due to occupants and electrical equipments, A_{int} (W), the solar gains, A_{sol} (W), and the treated air flow, m_t (kg.s^{-1}).

The modelling of solar gains depends on the direct and diffuse solar radiation, the position of the sun in the sky and the geometric and physical properties of the vehicle window (Fraisse and Virgone, 2001). The temperature and flow rate of the treated air are regulated in order to maintain the cabin air at the required temperature.

The thermal mass of the vehicle's interior has an effect on dynamic behaviour, such as increasing cooling demands during cool-down, but has no effect during steady-state cooling and was therefore neglected. Weilenmann *et al.* (2004) have studied initial cool-down by combining the effects of initial cool-down of the overheated passenger compartment with the effects of cold start. Two counteracting effects occur: (i) because of thermal mass, A/C running involves more power than steady-state, and (ii) A/C running requires that the engine compartment is heated much faster than without A/C running. These two effects compensate each other, and the excess emission due to initial cool-down (compared with the steady-state emission) is of the same order of magnitude as the cold-start excess emission under the same temperature conditions.

For an internal temperature T_{int}, the temperature of treated air T_t, and the outside temperature T_{ext}, the equation of energy conservation is:

$$\left(m_t + m_p\right)\cdot T_{int} - \left(m_t \cdot T_t + m_p \cdot T_{ext}\right) = A_{int} + UA\cdot\left(T_{ext} - T_{int}\right) + A_{sol}$$ (Equation B3-9)

The internal temperature is chosen according to the thermal comfort theory (Fanger, 1972). The conditions of thermal comfort are a combination of skin temperature and the body's core temperature providing a sensation of thermal neutrality and the fulfilment of the body's energy balance. From ASHRAE standard 55 (ASHRAE, 1992) and Charles (2003), 23°C was chosen as the default value. The sensible heat exchange $\boldsymbol{P_{sens}}$ at the evaporator to maintain the internal temperature at the comfort temperature can be deduced, and, if air treated rate $\boldsymbol{m_t}$ is known, the air treated temperature $\boldsymbol{T_t}$ can be calculated using the equation:

$$P_{sens} = m_t \cdot \left(T_{ext} - T_t\right) = \left(m_t + m_p + UA\right)\cdot\left(T_{ext} - T_{int}\right) + A_{sol} + A_{int}$$ (Equation B3-10)

Evaporator and A/C regulator modelling

Heat exchange at the evaporator can cause dehumidification of the treated air. The total heat exchange at the evaporator is the sum of sensible heat exchange and dehumidification. The average surface temperature of the air treated across the A/C evaporator depends on the heat transfer coefficients of the evaporator and the temperature of coolant. If the average surface temperature is known, the air-side heat exchange efficiency can be used to calculate the average surface temperature and humidity of the outlet air. The value of this efficiency is usually between 60% and 80% (Morisot, 2002). In the model, the value of the air side efficiency was assumed to be 80%.

It was assumed that the user or A/C regulator tries to maintain a minimum air flow rate (in order to reduce thermal load). On the other hand, the temperature of the treated air must not to be too low because of comfort considerations and the risk of freezing condensed water in the evaporator. A minimum air flow rate of 300 m^3/h and a minimum average surface temperature of 0°C were therefore assumed.

Energy efficiency of A/C and engine

It was assumed that the efficiencies of the A/C and the engine were constant. For the energy efficiency of the engine, experimental data show that the running conditions have a small effect on CO_2 emissions due to A/C. According to Park *et al.* (1999), the main parameter affecting A/C efficiency is the temperature, but the effects of temperature on energy efficiency are lower than the effects on cooling demands.

Validity of the model

The model was applied to all experimental conditions - either those described above or those given by Weilenmann *et al.* (2004), with temperature ranges of 28-40°C and 13-37°C respectively. The results of the model were compared with the experimental results (see **Figure B3-14**). The model predictions were quite close for temperatures higher than 30°C. Between 20°C and 30°C, the model underestimated fuel consumption, and below 20°C the hourly fuel consumption from the model was zero, but experimental excess fuel consumption could be linked to the operation of A/C to avoid windscreen fogging.

A further comparison was made with the USEPA's MOBILE 6 model, this time in terms of a 'demand factor' based on experimental measurements. The demand factor is defined in MOBILE 6 as the fraction of running time of A/C, but can also be defined as the ratio of part-load power consumption to the full-load power consumption (estimated at 0.85 l/h). The MOBILE 6 model and the proposed model were tested using hourly weather data for Seville in Spain, which was the European city having the closest climate to Denver, where the experiments had been conducted in order to determine the demand factor in MOBILE 6. In order to take into account solar load, MOBILE 6 distinguishes between daytime and night-time periods, and the ARTEMIS model calculates the solar load for each climatic condition described in the weather data. As shown in **Figure B3-15**, the demand factors obtained using MOBILE 6 and the ARTEMIS model were quite close for temperatures higher than 20°C. Below 20°C, the demand factor from MOBILE 6 was zero, but slightly higher than zero for the ARTEMIS model because of solar load heating.

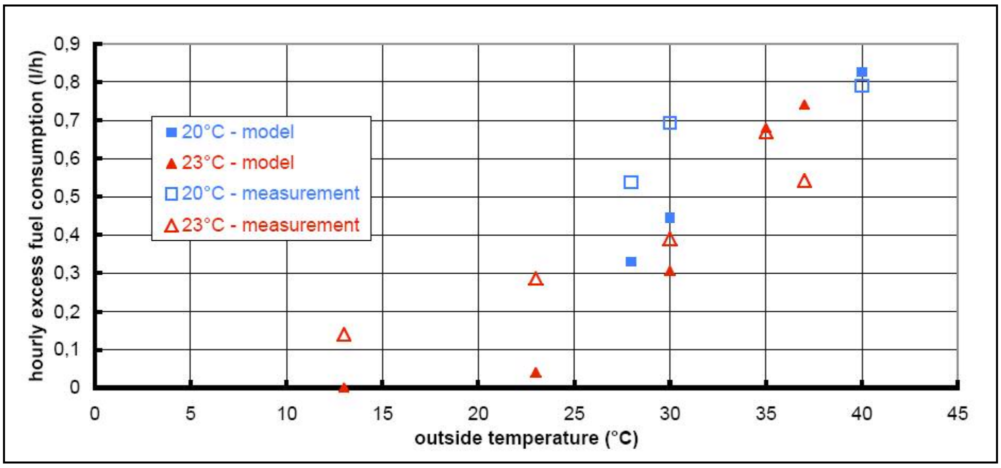

Figure B3-14: Comparison of the results from the model and from experiments as a function of outside temperature for two internal temperatures (20°C and 23°C).

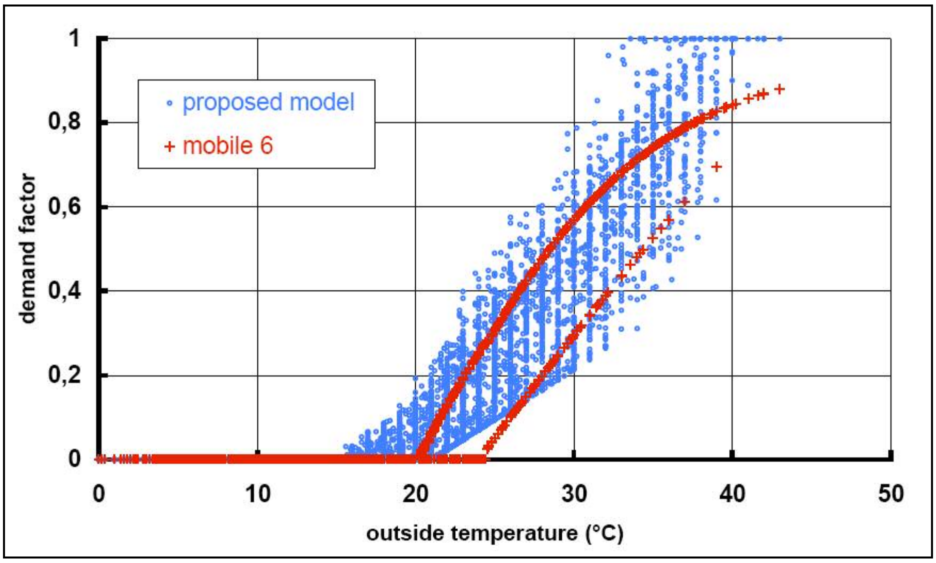

Figure B3-15: Comparison of the MOBLE 6 model (upper curve for daytime and lower curve for night-time) with the proposed ARTEMIS model (temperature = 23°C).

Simplified model and weather data

The full physical model of excess fuel consumption due to A/C was considered to be too complex to be implemented in the ARTEMIS inventory model. Therefore, the physical model was run using weather data for 91 regions of Europe, as defined in **Table B3-30**, and regression analysis was used to determine the relationship between hourly fuel consumption and the following variables: ambient temperature, humidity, position of the sun in the sky, and solar radiation (replaced by the hour of the day). The general form of the simplified model was:

$$hfc = a_{1,wf} + a_{2,wf} \cdot T_{ext,wf} + a_{3,wf} \cdot (T_{\text{int}} - 23) + a_{4,wf} \cdot h + a_{5,wf} \cdot h^2 \quad \text{with } hfc \geq 0 \qquad \text{(Equation B3-11)}$$

where:

hfc	=	hourly excess fuel consumption (l/h)
$T_{ext,wf}$	=	external temperature provided by hourly, daily or monthly weather data (°C)
T_{int}	=	required temperature in the cabin; the default value is 23°C
h	=	the hour (between 1 and 24)
$a_{1,...5}$	=	coefficients which depend upon the location

The coefficients a_1 to a_5 are given for each location in **Tables B3-31**to **B3-39**. In addition, two other sets of coefficient were used - the first set was a modified Köppen climate classification, based on the annual and monthly averages of temperature and precipitation (DoE, 2004), and the second set corresponded to average values.

Table B3-30: Characteristics of the 90 European cities considered for auxiliaries emission modelling (longitude, latitude, temperature and Köppen class).

ID	Country	City	Long.	Lat.	Köppen class	Average temp. (°C)	ID	Country	City	Long.	Lat.	Köppen class	Average temp. (°C)
1	AUT	GRAZ	15.43	47	Dfb	9.5	47	GBR	HEMSBY	1.68	52.68	Cfb	9.9
2	AUT	INNSBRUCK	11.35	47.27	Dfb	9.0	48	GBR	JERSEY/CHAN.	-2.2	49.22	Cfb	11.2
3	AUT	LINZ	14.2	48.23	Dfb	9.2	49	GBR	LEUCHARS	-2.87	56.38	Cfb	8.7
4	AUT	SALZBURG	13	47.8	Dfb	9.3	50	GBR	LONDON/GATWICK	-0.18	51.15	Cfb	10.2
5	AUT	VIENNA	16.57	48.12	Dfb	10.0	51	GBR	OBAN	-5.47	56.42	Cfb	9.3
6	BEL	BRUSSELS	4.53	50.9	Cfb	10.3	52	GRC	ANDRAVIDA	21.28	37.92	Csa	16.7
7	BEL	OOSTENDE	2.87	51.2	Cfb	10.3	53	GRC	ATHENS	23.73	37.9	Cfa	17.9
8	BEL	SAINT HUBERT	5.4	50.03	Dfb	7.5	54	GRC	THESSALONIKI	22.97	40.52	Cfa	15.4
9	CHE	GENEVA	6.13	46.25	Cfb	10.4	55	IRL	BELMULLET	-10	54.23	Cfb	10.3
10	CZE	OSTRAVA	18.18	49.72	Dfb	8.5	56	IRL	BIRR	-7.88	53.08	Cfb	9.6
11	CZE	PRAGUE	14.28	50.1	Dfb	8.1	57	IRL	CLONES	-7.23	54.18	Cfb	9.1
12	DEU	BERLIN	13.4	52.47	Cfb	9.8	58	IRL	DUBLIN	-6.25	53.43	Cfb	9.8
13	DEU	BREMEN	8.8	53.05	Cfb	8.9	59	IRL	KILKENNY	-7.27	52.67	Cfb	9.7
14	DEU	DUSSELDORF	6.78	51.28	Cfb	10.5	60	IRL	MALIN	-7.33	55.37	Cfb	9.7
15	DEU	FRANKFURT AM	8.6	50.05	Cfb	10.1	61	IRL	VALENTIA	-10.25	51.93	Cfb	11.0
16	DEU	HAMBURG	10	53.63	Cfb	9.0	62	ITA	BRINDISI	17.95	40.65	Cfa	17.1
17	DEU	KOLN	7.17	50.87	Cfb	9.9	63	ITA	GENOVA	8.85	44.42	Cfa	16.1
18	DEU	MANNHEIM	8.55	49.52	Cfb	11.1	64	ITA	MESSINA	15.55	38.2	Cfa	18.9
19	DEU	MUNICH	11.7	48.13	Dfb	8.0	65	ITA	MILAN	8.73	45.62	Cfa	11.8
20	DEU	STUTTGART	9.22	48.68	Dfb	9.1	66	ITA	NAPLES	14.3	40.85	Cfa	16.3
21	DNK	COPENHAGEN	12.67	55.63	Cfb	8.3	67	ITA	PALERMO	13.1	38.18	Cfa	18.8
22	ESP	BARCELONA	2.07	41.28	Cfa	15.7	68	ITA	PISA	10.38	43.68	Cfa	14.6
23	ESP	MADRID	-3.55	40.45	Cfa	14.3	69	ITA	ROME	12.23	41.8	Cfa	15.8
24	ESP	PALMA	2.73	39.55	Cfa	16.7	70	ITA	TORINO	7.65	45.22	Cfa	12.2
25	ESP	SANTANDER	-3.82	43.47	Cfb	14.8	71	ITA	VENICE	12.33	45.5	Cfa	13.2
26	ESP	SEVILLA	-5.9	37.42	Csa	18.4	72	NLD	AMSTERDAM	4.77	52.3	Cfb	10.0
27	ESP	VALENCIA	-0.47	39.5	Cfa	17.3	73	NLD	BEEK	5.78	50.92	Cfb	10.1
28	FIN	HELSINKI	24.97	60.32	Dfb	5.2	74	NLD	GRONINGEN	6.58	53.13	Cfb	9.1
29	FIN	TAMPERE	23.58	61.42	Dfb	4.3	75	POL	KOLOBRZEG	15.58	54.18	Dfb	8.5
30	FRA	BORDEAUX	-0.7	44.83	Cfb	13.2	76	POL	KRAKOW	19.8	50.08	Dfb	8.2
31	FRA	BREST	-4.42	48.45	Cfb	11.2	77	POL	POZNAN	16.83	52.42	Dfb	8.6
32	FRA	CLERMONT-	3.17	45.78	Cfb	11.4	78	POL	WARSAW	20.97	52.17	Dfb	8.4
33	FRA	DIJON	5.08	47.27	Cfb	10.7	79	PRT	BRAGANCA	-6.73	41.8	Cfb	12.4
34	FRA	LYON	5.08	45.73	Cfb	11.9	80	PRT	COIMBRA	-8.42	40.2	Csb	15.3
35	FRA	MARSEILLE	5.23	43.45	Cfa	14.8	81	PRT	EVORA	-7.9	38.57	Cfa	15.8
36	FRA	MONTPELLIER	3.97	43.58	Cfa	14.8	82	PRT	FARO	-7.97	37.02	Cfa	17.8
37	FRA	NANCY	6.22	48.68	Cfb	10.2	83	PRT	LAJES	-27.1	38.77	Cfa	17.5
38	FRA	NANTES	-1.6	47.17	Cfb	12.2	84	PRT	PORTO	-8.68	41.23	Csb	14.3
39	FRA	NICE	7.2	43.65	Cfa	15.5	85	SVK	BRATISLAVA	17.2	48.2	Dfb	10.4
40	FRA	PARIS_ ORLY	2.4	48.73	Cfb	11.1	86	SVK	KOSICE	21.27	48.7	Dfb	9.1
41	FRA	STRASBOURG	7.63	48.55	Cfb	10.3	87	SWE	GOTEBORG	12.3	57.67	Dfb	6.5
42	GBR	ABERDEEN/DYCE	-2.22	57.2	Cfb	8.4	88	SWE	KARLSTAD	13.47	59.37	Dfb	5.9
43	GBR	AUGHTON	-2.92	53.55	Cfb	9.5	89	SWE	KIRUNA	20.33	67.82	Dfc	-1.1
44	GBR	BELFAST	-6.22	54.65	Cfb	9.1	90	SWE	OSTERSUND/FROSON	14.5	63.18	Dfc	3.1
45	GBR	BIRMINGHAM	-1.73	52.45	Cfb	9.7	91	SWE	STOCKHOLM	17.95	59.65	Dfb	6.5
46	GBR	FINNINGLEY	-1	53.48	Cfb	9.5							

Table B3-31: Values of hourly fuel consumption in simplified model for hourly weather format for each location.

ID	a_1	a_2	a_3	a_4	a_5	ID	a_1	a_2	a_3	a_4	a_5
1	-0.863	0.0402	-0.0376	0.0334	-0.00164	47	-0.901	0.0358	-0.0311	0.0539	-0.00228
2	-0.722	0.0312	-0.0294	0.0355	-0.00160	48	-0.987	0.0366	-0.0332	0.0672	-0.00277
3	-0.731	0.0332	-0.0326	0.0348	-0.00168	49	-0.814	0.0330	-0.0279	0.0458	-0.00191
4	-0.834	0.0362	-0.0339	0.0383	-0.00176	50	-0.840	0.0333	-0.0310	0.0500	-0.00218
5	-0.808	0.0355	-0.0329	0.0360	-0.00164	51	-0.725	0.0263	-0.0229	0.0494	-0.00198
6	-0.890	0.0386	-0.0349	0.0391	-0.00171	52	-0.967	0.0419	-0.0404	0.0380	-0.00163
7	-0.946	0.0370	-0.0330	0.0556	-0.00226	53	-0.947	0.0374	-0.0382	0.0483	-0.00197
8	-0.818	0.0302	-0.0281	0.0536	-0.00217	54	-0.903	0.0368	-0.0377	0.0461	-0.00195
9	-0.799	0.0346	-0.0333	0.0386	-0.00172	55	-0.786	0.0296	-0.0237	0.0502	-0.00199
10	-0.831	0.0364	-0.0336	0.0377	-0.00176	56	-0.867	0.0339	-0.0285	0.0504	-0.00207
11	-0.799	0.0345	-0.0323	0.0385	-0.00176	57	-1.031	0.0362	-0.0307	0.0681	-0.00269
12	-0.732	0.0319	-0.0300	0.0344	-0.00155	58	-0.883	0.0332	-0.0284	0.0548	-0.00220
13	-0.842	0.0363	-0.0355	0.0406	-0.00182	59	-0.913	0.0341	-0.0305	0.0575	-0.00236
14	-0.761	0.0322	-0.0306	0.0356	-0.00154	60	-0.682	0.0217	-0.0243	0.0541	-0.00213
15	-0.797	0.0345	-0.0322	0.0377	-0.00170	61	-0.910	0.0338	-0.0283	0.0594	-0.00234
16	-0.829	0.0353	-0.0324	0.0399	-0.00174	62	-1.262	0.0543	-0.0461	0.0495	-0.00209
17	-0.755	0.0326	-0.0315	0.0367	-0.00166	63	-1.195	0.0488	-0.0426	0.0523	-0.00208
18	-0.786	0.0342	-0.0335	0.0359	-0.00163	64	-1.106	0.0468	-0.0443	0.0461	-0.00191
19	-0.799	0.0334	-0.0319	0.0440	-0.00197	65	-0.953	0.0411	-0.0388	0.0409	-0.00179
20	-0.763	0.0328	-0.0319	0.0396	-0.00181	66	-1.018	0.0448	-0.0422	0.0382	-0.00166
21	-0.794	0.0307	-0.0284	0.0484	-0.00201	67	-1.174	0.0485	-0.0441	0.0527	-0.00213
22	-1.110	0.0461	-0.0416	0.0481	-0.00192	68	-0.945	0.0415	-0.0405	0.0399	-0.00172
23	-0.822	0.0331	-0.0338	0.0437	-0.00185	69	-1.105	0.0478	-0.0436	0.0420	-0.00172
24	-1.182	0.0504	-0.0450	0.0471	-0.00192	70	-1.033	0.0458	-0.0411	0.0410	-0.00180
25	-0.968	0.0393	-0.0344	0.0484	-0.00189	71	-1.065	0.0468	-0.0411	0.0367	-0.00158
26	-0.924	0.0383	-0.0391	0.0407	-0.00176	72	-0.900	0.0358	-0.0323	0.0502	-0.00206
27	-1.060	0.0454	-0.0408	0.0408	-0.00169	73	-0.852	0.0369	-0.0345	0.0394	-0.00173
28	-0.793	0.0291	-0.0292	0.0517	-0.00211	74	-0.927	0.0398	-0.0350	0.0443	-0.00192
29	-0.729	0.0277	-0.0283	0.0461	-0.00190	75	-0.772	0.0295	-0.0314	0.0515	-0.00218
30	-0.877	0.0355	-0.0354	0.0458	-0.00192	76	-0.801	0.0362	-0.0338	0.0359	-0.00174
31	-1.192	0.0370	-0.0328	0.0888	-0.00332	77	-0.753	0.0342	-0.0323	0.0319	-0.00152
32	-0.802	0.0336	-0.0332	0.0408	-0.00178	78	-0.792	0.0359	-0.0338	0.0352	-0.00169
33	-0.927	0.0400	-0.0377	0.0440	-0.00196	79	-0.721	0.0299	-0.0314	0.0412	-0.00180
34	-0.898	0.0375	-0.0373	0.0442	-0.00191	80	-0.993	0.0400	-0.0376	0.0544	-0.00231
35	-0.989	0.0408	-0.0384	0.0469	-0.00195	81	-0.776	0.0305	-0.0336	0.0472	-0.00199
36	-0.924	0.0390	-0.0375	0.0413	-0.00172	82	-0.970	0.0384	-0.0375	0.0552	-0.00224
37	-0.871	0.0377	-0.0342	0.0406	-0.00182	83	-1.128	0.0472	-0.0393	0.0442	-0.00174
38	-0.855	0.0343	-0.0345	0.0477	-0.00200	84	-0.963	0.0368	-0.0347	0.0596	-0.00240
39	-1.143	0.0468	-0.0413	0.0536	-0.00215	85	-0.869	0.0384	-0.0367	0.0373	-0.00173
40	-0.861	0.0367	-0.0346	0.0416	-0.00183	86	-0.818	0.0362	-0.0345	0.0375	-0.00175
41	-0.923	0.0416	-0.0365	0.0389	-0.00181	87	-0.783	0.0265	-0.0255	0.0582	-0.00234
42	-1.062	0.0394	-0.0327	0.0662	-0.00274	88	-0.860	0.0324	-0.0316	0.0564	-0.00235
43	-0.791	0.0308	-0.0264	0.0491	-0.00203	89	-0.620	0.0221	-0.0227	0.0441	-0.00183
44	-0.786	0.0313	-0.0271	0.0462	-0.00192	90	-0.670	0.0263	-0.0273	0.0421	-0.00178
45	-0.804	0.0305	-0.0289	0.0523	-0.00223	91	-0.729	0.0296	-0.0280	0.0421	-0.00185
46	-0.735	0.0294	-0.0264	0.0428	-0.00186						

Table B3-32: Values of hourly fuel consumption in simplified model for daily weather format for each location.

ID	a_1	a_2	a_3	a_4	a_5	ID	a_1	a_2	a_3	a_4	a_5
1	-1.286	0.0342	-0.0321	0.1281	-0.00477	47	-0.953	0.0300	-0.0242	0.0891	-0.00352
2	-0.869	0.0256	-0.0224	0.0825	-0.00300	48	-1.098	0.0352	-0.0254	0.0986	-0.00381
3	-1.119	0.0311	-0.0272	0.1071	-0.00394	49	-1.010	0.0285	-0.0201	0.0974	-0.00360
4	-1.189	0.0326	-0.0279	0.1157	-0.00429	50	-1.441	0.0335	-0.0258	0.1507	-0.00551
5	-1.099	0.0333	-0.0290	0.0971	-0.00364	51	-0.769	0.0197	-0.0127	0.0760	-0.00267
6	-1.245	0.0385	-0.0282	0.1039	-0.00375	52	-1.249	0.0383	-0.0360	0.1096	-0.00411
7	-1.071	0.0356	-0.0259	0.0894	-0.00331	53	-1.059	0.0327	-0.0351	0.0923	-0.00350
8	-0.873	0.0244	-0.0223	0.0836	-0.00302	54	-1.075	0.0320	-0.0336	0.0970	-0.00359
9	-1.118	0.0313	-0.0278	0.1043	-0.00375	55	-0.632	0.0177	-0.0132	0.0655	-0.00252
10	-1.125	0.0324	-0.0265	0.1141	-0.00440	56	-1.035	0.0284	-0.0187	0.0977	-0.00350
11	-1.296	0.0332	-0.0270	0.1311	-0.00488	57	-1.244	0.0267	-0.0208	0.1318	-0.00469
12	-0.952	0.0298	-0.0252	0.0817	-0.00303	58	-0.919	0.0262	-0.0208	0.0841	-0.00303
13	-1.390	0.0359	-0.0299	0.1353	-0.00490	59	-1.042	0.0250	-0.0190	0.1101	-0.00399
14	-0.891	0.0273	-0.0237	0.0785	-0.00287	60	-0.749	0.0227	-0.0195	0.0700	-0.00273
15	-1.039	0.0304	-0.0253	0.0945	-0.00341	61	-0.792	0.0249	-0.0190	0.0723	-0.00270
16	-1.079	0.0310	-0.0258	0.0996	-0.00363	62	-1.430	0.0496	-0.0415	0.1031	-0.00393
17	-1.115	0.0301	-0.0244	0.1073	-0.00386	63	-1.182	0.0419	-0.0380	0.0806	-0.00304
18	-1.135	0.0325	-0.0277	0.1057	-0.00389	64	-1.195	0.0438	-0.0419	0.0782	-0.00305
19	-1.194	0.0308	-0.0263	0.1244	-0.00459	65	-1.057	0.0300	-0.0330	0.1060	-0.00392
20	-1.318	0.0318	-0.0264	0.1340	-0.00481	66	-1.223	0.0394	-0.0376	0.1024	-0.00389
21	-0.936	0.0273	-0.0230	0.0892	-0.00338	67	-1.214	0.0445	-0.0408	0.0790	-0.00302
22	-1.069	0.0355	-0.0345	0.0887	-0.00331	68	-1.148	0.0365	-0.0349	0.0997	-0.00369
23	-1.040	0.0288	-0.0282	0.0982	-0.00346	69	-1.205	0.0396	-0.0371	0.1017	-0.00385
24	-1.266	0.0399	-0.0374	0.1188	-0.00449	70	-1.169	0.0373	-0.0353	0.0989	-0.00361
25	-0.945	0.0333	-0.0279	0.0709	-0.00265	71	-1.218	0.0417	-0.0363	0.0857	-0.00316
26	-1.301	0.0358	-0.0326	0.1179	-0.00418	72	-1.122	0.0347	-0.0246	0.0999	-0.00371
27	-1.110	0.0361	-0.0333	0.0934	-0.00344	73	-1.081	0.0346	-0.0275	0.0913	-0.00337
28	-1.118	0.0287	-0.0247	0.1105	-0.00401	74	-1.189	0.0359	-0.0259	0.1104	-0.00410
29	-0.993	0.0251	-0.0236	0.0992	-0.00355	75	-0.944	0.0310	-0.0261	0.0836	-0.00330
30	-1.150	0.0325	-0.0292	0.1063	-0.00381	76	-1.339	0.0364	-0.0288	0.1328	-0.00503
31	-1.559	0.0330	-0.0244	0.1633	-0.00576	77	-1.086	0.0323	-0.0270	0.1008	-0.00379
32	-1.136	0.0306	-0.0277	0.1104	-0.00399	78	-1.185	0.0340	-0.0284	0.1162	-0.00445
33	-1.319	0.0366	-0.0315	0.1235	-0.00446	79	-1.066	0.0280	-0.0269	0.1079	-0.00391
34	-1.207	0.0348	-0.0317	0.1100	-0.00401	80	-1.438	0.0370	-0.0312	0.1448	-0.00532
35	-1.133	0.0344	-0.0328	0.1032	-0.00386	81	-1.109	0.0300	-0.0293	0.1070	-0.00389
36	-1.128	0.0349	-0.0325	0.1009	-0.00378	82	-1.051	0.0335	-0.0332	0.0945	-0.00361
37	-1.146	0.0327	-0.0269	0.1089	-0.00394	83	-1.021	0.0382	-0.0312	0.0670	-0.00257
38	-1.195	0.0325	-0.0294	0.1118	-0.00399	84	-1.127	0.0335	-0.0293	0.1087	-0.00412
39	-1.169	0.0386	-0.0366	0.0958	-0.00362	85	-1.284	0.0368	-0.0331	0.1225	-0.00467
40	-1.129	0.0333	-0.0280	0.0990	-0.00355	86	-1.199	0.0335	-0.0308	0.1202	-0.00467
41	-1.377	0.0392	-0.0296	0.1269	-0.00460	87	-1.129	0.0271	-0.0206	0.1193	-0.00441
42	-1.458	0.0378	-0.0243	0.1503	-0.00576	88	-1.008	0.0257	-0.0261	0.1027	-0.00376
43	-0.873	0.0265	-0.0188	0.0794	-0.00296	89	-0.715	0.0175	-0.0183	0.0773	-0.00290
44	-0.768	0.0197	-0.0171	0.0776	-0.00283	90	-0.930	0.0230	-0.0223	0.0940	-0.00336
45	-1.317	0.0305	-0.0239	0.1376	-0.00504	91	-1.065	0.0281	-0.0241	0.1055	-0.00393
46	-1.135	0.0275	-0.0204	0.1190	-0.00436						

Table B3-33: Values of hourly fuel consumption in simplified model for monthly weather format for each location.

ID	a_1	a_2	a_3	a_4	a_5	ID	a_1	a_2	a_3	a_4	a_5
1	-0.403	0.0138	-0.0067	0.0493	-0.00186	47	-0.233	0.0118	-0.0043	0.0196	-0.00080
2	-0.219	0.0090	-0.0043	0.0259	-0.00096	48	-0.301	0.0131	-0.0052	0.0282	-0.00110
3	-0.345	0.0132	-0.0058	0.0381	-0.00142	49	-0.283	0.0084	-0.0031	0.0321	-0.00118
4	-0.301	0.0106	-0.0047	0.0381	-0.00142	50	-0.508	0.0149	-0.0054	0.0548	-0.00193
5	-0.371	0.0148	-0.0060	0.0392	-0.00148	51	-0.133	0.0049	-0.0020	0.0129	-0.00045
6	-0.258	0.0114	-0.0041	0.0252	-0.00091	52	-0.722	0.0266	-0.0101	0.0683	-0.00254
7	-0.293	0.0126	-0.0049	0.0267	-0.00098	53	-0.755	0.0269	-0.0116	0.0707	-0.00263
8	-0.149	0.0058	-0.0034	0.0182	-0.00068	54	-0.676	0.0230	-0.0104	0.0705	-0.00259
9	-0.425	0.0160	-0.0063	0.0443	-0.00163	55	-0.212	0.0053	-0.0027	0.0256	-0.00096
10	-0.322	0.0129	-0.0051	0.0375	-0.00144	56	-0.193	0.0085	-0.0033	0.0177	-0.00066
11	-0.289	0.0107	-0.0050	0.0352	-0.00134	57	-0.304	0.0084	-0.0034	0.0337	-0.00118
12	-0.279	0.0118	-0.0051	0.0286	-0.00107	58	-0.170	0.0079	-0.0034	0.0152	-0.00057
13	-0.254	0.0107	-0.0045	0.0284	-0.00106	59	-0.240	0.0124	-0.0042	0.0191	-0.00073
14	-0.235	0.0101	-0.0044	0.0248	-0.00093	60	-0.180	0.0052	-0.0022	0.0202	-0.00076
15	-0.307	0.0123	-0.0051	0.0331	-0.00122	61	-0.154	0.0079	-0.0036	0.0125	-0.00047
16	-0.216	0.0092	-0.0044	0.0243	-0.00091	62	-0.852	0.0344	-0.0127	0.0702	-0.00265
17	-0.247	0.0100	-0.0048	0.0275	-0.00101	63	-0.585	0.0256	-0.0104	0.0469	-0.00177
18	-0.386	0.0150	-0.0060	0.0409	-0.00152	64	-0.729	0.0329	-0.0130	0.0497	-0.00195
19	-0.336	0.0120	-0.0054	0.0416	-0.00157	65	-0.666	0.0212	-0.0101	0.0755	-0.00278
20	-0.364	0.0132	-0.0055	0.0407	-0.00149	66	-0.820	0.0302	-0.0119	0.0760	-0.00286
21	-0.246	0.0106	-0.0044	0.0246	-0.00096	67	-0.691	0.0319	-0.0120	0.0461	-0.00176
22	-0.705	0.0260	-0.0110	0.0655	-0.00239	68	-0.589	0.0228	-0.0098	0.0579	-0.00212
23	-0.629	0.0201	-0.0084	0.0648	-0.00222	69	-0.712	0.0275	-0.0109	0.0674	-0.00253
24	-0.796	0.0304	-0.0120	0.0764	-0.00285	70	-0.632	0.0225	-0.0099	0.0646	-0.00233
25	-0.394	0.0171	-0.0061	0.0322	-0.00119	71	-0.645	0.0253	-0.0109	0.0553	-0.00203
26	-0.833	0.0273	-0.0113	0.0779	-0.00271	72	-0.252	0.0106	-0.0044	0.0266	-0.00100
27	-0.803	0.0290	-0.0115	0.0718	-0.00256	73	-0.282	0.0117	-0.0049	0.0289	-0.00105
28	-0.220	0.0088	-0.0043	0.0253	-0.00095	74	-0.221	0.0097	-0.0041	0.0240	-0.00089
29	-0.213	0.0084	-0.0042	0.0243	-0.00090	75	-0.187	0.0082	-0.0044	0.0207	-0.00080
30	-0.495	0.0177	-0.0070	0.0520	-0.00189	76	-0.294	0.0120	-0.0052	0.0347	-0.00134
31	-0.368	0.0134	-0.0050	0.0355	-0.00128	77	-0.262	0.0111	-0.0050	0.0298	-0.00114
32	-0.383	0.0138	-0.0057	0.0445	-0.00163	78	-0.328	0.0132	-0.0054	0.0371	-0.00143
33	-0.485	0.0176	-0.0070	0.0523	-0.00192	79	-0.504	0.0178	-0.0065	0.0547	-0.00200
34	-0.444	0.0168	-0.0067	0.0472	-0.00173	80	-0.538	0.0211	-0.0073	0.0527	-0.00197
35	-0.641	0.0232	-0.0094	0.0656	-0.00245	81	-0.646	0.0232	-0.0080	0.0606	-0.00221
36	-0.623	0.0227	-0.0089	0.0639	-0.00239	82	-0.717	0.0275	-0.0109	0.0637	-0.00240
37	-0.372	0.0154	-0.0057	0.0384	-0.00143	83	-0.597	0.0275	-0.0087	0.0358	-0.00137
38	-0.414	0.0157	-0.0063	0.0420	-0.00153	84	-0.536	0.0226	-0.0067	0.0474	-0.00182
39	-0.702	0.0271	-0.0105	0.0641	-0.00241	85	-0.523	0.0176	-0.0073	0.0614	-0.00232
40	-0.425	0.0160	-0.0062	0.0417	-0.00151	86	-0.473	0.0178	-0.0069	0.0516	-0.00200
41	-0.503	0.0189	-0.0067	0.0515	-0.00190	87	-0.208	0.0045	-0.0034	0.0291	-0.00105
42	-0.278	0.0069	-0.0029	0.0363	-0.00139	88	-0.252	0.0090	-0.0050	0.0300	-0.00112
43	-0.123	0.0061	-0.0024	0.0110	-0.00042	89	-0.103	0.0028	-0.0018	0.0145	-0.00055
44	-0.122	0.0055	-0.0026	0.0115	-0.00043	90	-0.116	0.0055	-0.0023	0.0125	-0.00045
45	-0.329	0.0119	-0.0045	0.0346	-0.00128	91	-0.196	0.0069	-0.0040	0.0250	-0.00093
46	-0.272	0.0110	-0.0040	0.0280	-0.00106						

Table B3-34: Values of hourly fuel consumption in simplified model for hourly weather format for Köppen classes.

Köppen classes	*a1*	*a2*	*a3*	*a4*	*a5*
Cfa	-1.0368	0.0436	-0.0404	0.0455	-0.00189
Cfb	-0.8575	0.0343	-0.0315	0.0480	-0.00202
Csa/Csb	-0.9618	0.0393	-0.0380	0.0482	-0.00203
Dfb	-0.7937	0.0333	-0.0319	0.0417	-0.00185
Dfc	-0.6450	0.0242	-0.0250	0.0431	-0.00181

Table B3-35: Values of hourly fuel consumption in simplified model for daily weather format for Köppen classes.

Köppen classes	*a1*	*a2*	*a3*	*a4*	*a5*
Cfa	-1.1486	0.0372	-0.0352	0.0951	-0.00356
Cfb	-1.0914	0.0305	-0.0243	0.1032	-0.00378
Csa/Csb	-1.2800	0.0362	-0.0323	0.1205	-0.00443
Dfb	-1.1300	0.0309	-0.0267	0.1110	-0.00414
Dfc	-0.8225	0.0203	-0.0203	0.0857	-0.00313

Table B3-36: Values of hourly fuel consumption in simplified model for monthly weather format for Köppen classes.

Köppen classes	*a1*	*a2*	*a3*	*a4*	*a5*
Cfa	-0.6914	0.0264	-0.0106	0.0629	-0.00233
Cfb	-0.3029	0.0117	-0.0046	0.0313	-0.00116
Csa/Csb	-0.6573	0.0244	-0.0088	0.0616	-0.00226
Dfb	-0.2979	0.0111	-0.0051	0.0349	-0.00132
Dfc	-0.1095	0.0041	-0.0020	0.0135	-0.00050

Table B3-37: Average values of hourly fuel consumption simplified model for hourly weather format.

a1	*a2*	*a3*	*a4*	*a5*
-0.886	0.0363	-0.0339	0.0458	-0.00195

Table B3-38: Average values of hourly fuel consumption simplified model for daily weather format.

a1	*a2*	*a3*	*a4*	*a5*
-1.116	0.0322	-0.0278	0.1034	-0.00382

Table B3-39: Average values of hourly fuel consumption simplified model for monthly weather format.

a1	*a2*	*a3*	*a4*	*a5*
-0.407	0.0155	-0.00631	0.04068	-0.00151

The excess fuel consumption and CO_2 emission for a fleet was calculated by summing the ***hfc*** values according to the number of vehicles with A/C running for a given road segment, expressed as the number of vehicles per hour. The general equation to calculate the excess fuel consumption fc_f for a fleet f due to the use of A/C is:

$$fc_f = \sum_{loc}\sum_{T}\sum_{TS}\sum_{i} n_{AC,i,TS,T,loc} \cdot hfc\left(h, T_{ext}, T_{\mathrm{int}}\right) \qquad \text{(Equation B3-12)}$$

The excess CO_2 emission is given by:

$$eCO_{2\,f} = \sum_{loc}\sum_{T}\sum_{TS}\sum_{i} n_{AC,i,TS,T,loc} \cdot c_{CO_2,i} \cdot hfc\left(h, T_{ext}, T_{\mathrm{int}}\right) \qquad \text{(Equation B3-13)}$$

where:

$n_{ac,i,TS,T,loc}$ = Number of vehicles with A/C running for segment ***i***, at the traffic situation ***TS*** (*i.e.* urban, rural, motorway), at the time ***T***, at the location ***loc***, expressed in number of vehicle per hour.

$$n_{AC,i,TS,T,loc} = n_{i,TS,T,loc} \cdot f_{clim,i} \qquad \text{(Equation B3-14)}$$

hfc = Hourly fuel consumption depending on the hour of the day, external temperature and internal temperature (l/h).

$c_{CO2,i}$ = Transformation factor from fuel to CO_2 depending on vehicle segment ***i***. The transformation factor was deduced from a carbon balance equation and the density of fuel. To calculate this factor, the mass of non-CO_2 pollutants was assumed to be negligible compared with the mass of CO_2.

$$c_{CO_2,i} = \frac{m_{CO_2}}{v_{fuel}} = \frac{44.011}{12.011 + 1.008 \cdot r_{H/C,i}} \cdot \rho_{fuel,i} \qquad \text{(Equation B3-15)}$$

$r_{H/C,i}$ = Hydrogen:carbon ratio, depending of the type of fuel (1.8 for petrol and 2 for diesel).

$\rho_{fuel,i}$ = Density of fuel (kg/l): 0.766 kg/l for petrol and 0.8414 kg/l for diesel.

$f_{clim,i}$ = Fraction of vehicles equipped with A/C in segment ***i***. The fraction of vehicles equipped with A/C was calculated with the penetration rate ($pr_{A/C,i}$).

$n_{i,TS,T,loc}$ = Number of vehicles belonging to segment ***i***, at the situation of traffic ***TS***, at time ***T***, and at location ***loc***:

$$n_{i,TS,T,loc} = \frac{n_{i,loc} \cdot k_{i,loc,TS}}{v_{TS}} \cdot d_{i,TS,T,loc} \qquad \text{(Equation B3-16)}$$

$n_{i,loc}$ = Total number of vehicles belonging to the segment ***i***, at the location ***loc***.

$k_{i,TS,loc}$ = Annual mileage of a vehicle belonging to the segment ***i***, in the traffic situation ***TS***, at the location ***loc*** (km).

v_{TS} = Mean speed of traffic situation ***TS*** (km/h).

$d_{i,TS,T,loc}$ = Traffic distribution coefficient (some examples are given in **Figure B3-16**)

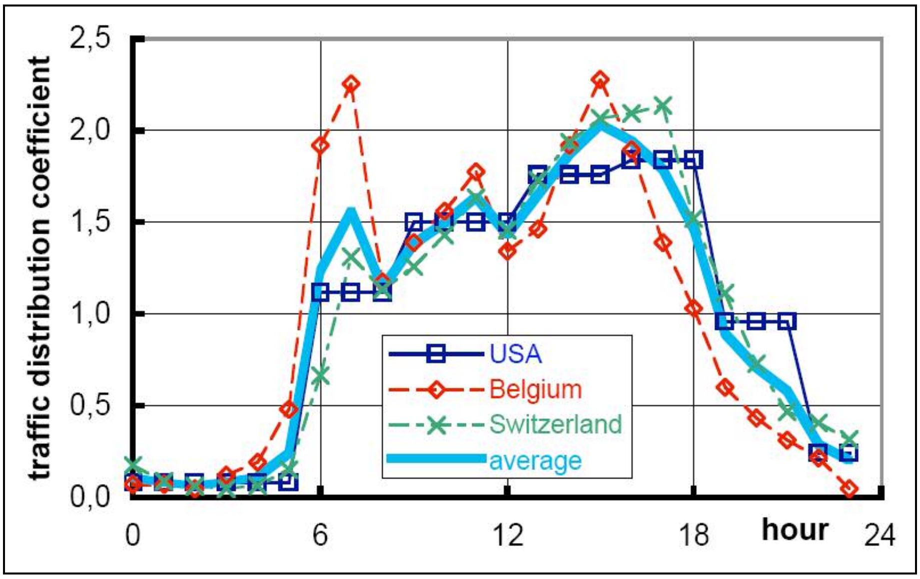

Figure B3-16: Traffic distribution coefficients (% of the hourly average).

Excess pollutant emissions

Few data were available on A/C effects for regulated pollutants (CO, HC, NO_x, PM) compared with CO_2, mainly because only 13 petrol and diesel vehicles were tested. The A/C systems were running close to the full load at the test conditions (outside temperature > 28°C), and pollutants emissions were assumed to be those at full load. Examples of the data for NO_x are shown in **Figure B3-17**.

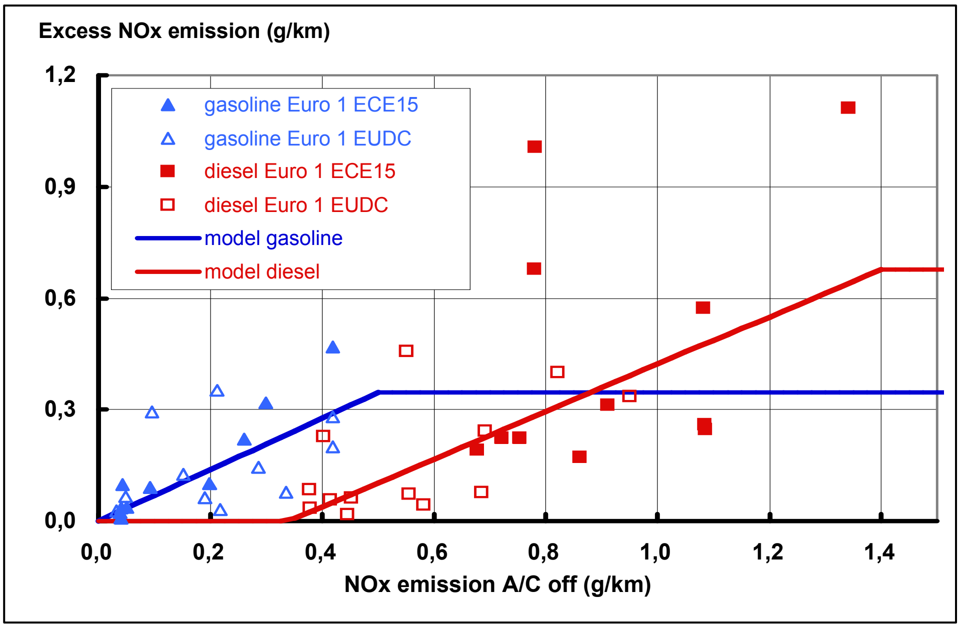

Figure B3-17: Excess NO_x emission versus NO_x emission. A/C off according to the fuel and driving cycle for Euro I vehicles, for urban ECE15 and extra-urban EUDC driving cycles, with the corresponding modelling.

NO_x emissions and the effects of A/C were larger during the urban driving cycle (ECE15) than during the extra-urban cycle (EUDC). For each pollutant, a relationship has been proposed between the excess exhaust emission and the hot exhaust emission without A/C, as in the Figure. These relationships are described in **Table B3-40**. The results for petrol vehicles are in accordance with the theoretical explanation proposed by Soltic and Weilenmann (2002). In other words, as long as the increased torque does not cause an air-fuel mixture enrichment, then an increase in the exhaust temperature, slight reductions of HC and CO emissions, and an increase in NO_x emission are to be expected. If an increased torque level causes an increase in enrichment, then CO and HC emissions will also increase.

For the modelling of pollutant emissions, it has been assumed that the emissions at part load ($ef_{pollutant, AC}$) are a fraction of the emissions at full load (***f(hot emission without AC)***), with the fraction being equal to the demand factor. The demand factor is the ratio of hourly fuel consumption at given condition hfc to hourly fuel consumption at full load (0.85 l/h).

$$ef_{pollutant,\ AC} = f\,(\textit{hot emission without AC})\ .\ hfc\ /\ 0.85 \qquad \text{(Equation B3-17)}$$

Because of the lack of data, only a distinction between petrol and diesel vehicles is proposed. The model does not explicitly define the age of vehicle, because it is considered to exert no influence on excess CO_2 emissions. The effects of emission standard on pollutant emission are taken into account through the use of standard hot exhaust emission factors.

For future vehicles, counteracting effects will occur. Firstly, technological improvements in the efficiency of A/C system are expected by reducing the thermal load of the vehicle (Türler *et al.*, 2003; Farrington *et al.*, 1998, 1999), and by increasing energy efficiency ratio of the A/C system (Benouali *et al.*, 2002; Barbusse and Gagnepain, 2003). Secondly, the evolution of vehicle design and in the leakage refrigerant standard will certainly increase CO_2 emissions due to the use of A/C. In the short term, it is assumed that these two effects compensate one another, and no correction is proposed for future vehicles.

Table B3-40: Relationships between the excess exhaust emission (CO, HC, NO_x) at full load and the hot exhaust emission without A/C.

Pollutant	Fuel	Function
CO	Petrol	If $ef_{CO,A/Coff}$<0.6 $cf_{AC,CO,diesel}\left(ef_{CO,ACoff}\right)=5/6\cdot ef_{CO,ACoff}$ else $cf_{AC,CO,gasoline}\left(ef_{CO,ACoff}\right)=0.5$
	Diesel	If $ef_{CO,A/Coff}$<1.56 $cf_{AC,CO,diesel}\left(ef_{CO,ACoff}\right)=-0.2825\cdot ef_{CO,ACoff}$ else $cf_{AC,CO,diesel}\left(ef_{CO,ACoff}\right)=-0.2825\cdot 1.56=-0.441$
HC	Petrol	If $ef_{HC,A/Coff}$<0.06g/km $cf_{AC,HC,gasoline}\left(ef_{HC,ACoff}\right)=1.21646\cdot ef_{HC,ACoff}$ If $ef_{HC,A/Coff}$>0.06g/km and <0.08 $cf_{AC,HC,gasoline}\left(ef_{HC,ACoff}\right)=0.072988$ If $ef_{HC,A/Coff}$ >0.08 and <0.944g/km $cf_{AC,HC,gasoline}\left(ef_{HC,ACoff}\right)=-0.2864\cdot ef_{HC,ACoff}+0.0959$ If $ef_{HC,A/Coff}$ >0.944g/km $cf_{AC,HC,gasoline}\left(ef_{HC,ACoff}\right)=-0.2864\cdot 0.944+0.0959=-0.174$
	Diesel	If $ef_{HC,A/Coff}$<0.857g/km $cf_{AC,HC,diesel}\left(ef_{HC,ACoff}\right)=-0.2743\cdot ef_{HC,ACoff}$ else $cf_{AC,HC,diesel}\left(ef_{HC,ACoff}\right)=-0.2743\cdot 0.855=-0.235$
NOx	Petrol	If $ef_{NOx,\ A/Coff}$< 0.5g/km $cf_{AC,NOx,gasoline}\left(ef_{NOx,ACoff}\right)=0.6918\cdot ef_{NOx,ACoff}$ else $cf_{AC,NOx,gasoline}\left(ef_{NOx,ACoff}\right)=0.6918\cdot 0.5=0.3459$
	Diesel	If $ef_{NOx,A/Coff}$<0.3397 $cf_{AC,NOx,diesel}\left(ef_{NOx,ACoff}\right)=0$ else if $ef_{NOx,A/Coff}$>0.3397 and $ef_{NOx,A/Coff}$<1.4 $cf_{AC,NOx,diesel}\left(ef_{NOx,ACoff}\right)=0.6395\cdot ef_{NOx,ACoff}-0.2172$ else $cf_{AC,NOx,diesel}\left(ef_{NOx,ACoff}\right)=0.6395\cdot 1.4-0.2172=0.6781$
PM	Petrol	$cf_{AC,Pa,gasoline}\left(ef_{NOx,ACoff}\right)=0$
	Diesel	If $ef_{HC,A/Coff}$< 0.2 g/km $cf_{AC,Pa,diesel}\left(ef_{HC,ACoff}\right)=0.3722\cdot ef_{HC,ACoff}$ else $cf_{AC,Pa,diesel}\left(ef_{HC,ACoff}\right)=0.07444$

Other auxiliary systems

The effects of other auxiliary systems on emissions were determined based on the work done by Soltic and Weilenmann (2002). Excess fuel consumption due to other auxiliary systems (***hfc_{aux}***) was expressed in litres per hour, as for A/C, and it was assumed that excess fuel consumption was proportional to electrical load. An average excess fuel consumption of 0.075 l/h was assumed for an electrical load of 160 W, corresponding to dipped headlights.

hfc_{aux}* (l/h) = *0.075* (l/h) . *Power of the auxiliaries* (W) / 160 (W) . *% of use time (Equation B3-18)

Table B3-41 lists auxiliary systems, and gives electrical power consumption. The group of auxiliary systems in the Table excludes some other important electrical power consumers, such as components linked to the engine or linked to security.

In order to be in accordance with the excess pollutant emission due to A/C, a similar method has been adopted for excess emissions due to other auxiliaries (***$ef_{pollutant,\ aux}$***). The excess pollutant emission due to A/C under a given condition is a fraction of the excess emission at full load. This fraction is calculated as the ratio of excess fuel consumption for the given condition (***hfc_{aux}***) to the excess fuel consumption at full load, estimated at 0.85 l/h (see above). However, the excess fuel consumption of A/C is replaced by the excess fuel consumption of the other auxiliary. For instance, when dipped headlights are used the value of the fraction is 0.075/0.85.

$$ef_{pollutant,\ aux} = f\ (hot\ emission\ without\ AC)\ .\ hfc_{aux}\ /\ 0.85 \quad \text{with}\ \ hfc_{aux}\ /\ 0.85 \leq 1 \qquad \text{(Equation B3-19)}$$

Table B3-41: Power consumption and estimated use of auxiliary systems (Soltic and Weilenmann, 2002).

Auxiliary	Electrical consumption (W)	Use of auxiliary (time proportion)
Dipped headlights	160	during night
Full headlight	170	
Turn indicator / stop light	40	1%
Fresh air ventilator	60	50%
Wipers	60	
Radio	15	85%
Rear window defroster	150	50% if outside temperature < 0°C
Seat heating	150	1%

Conclusions

The different analyses have shown that the excess fuel consumption - expressed in l/h - is independent of vehicle speed or the traffic situation, and no technological parameters exert a significant influence. This does not mean that no relationships exist between excess fuel consumption and technological parameters, only that the number of measurements was insufficient to extract this type of relationship, or that the technological effects overlap.

The excess fuel consumption due to A/C is well known in warm climates, and because of the large number of experiments. However, it is not so well defined for cooler climates because there are fewer data. To assess the behaviour of A/C systems under these conditions, a physical model was developed, and the model was compared with experimental data. The results showed a good agreement with measurements for warm climate conditions. For cooler climates, the model underestimated the excess fuel consumption without the reason being fully understood. In the model, based on the thermal comfort theory, it is assumed that the required temperature is 23°C for all the vehicles equipped with A/C, but experiments on real-world vehicles with A/C in cool climates could improve the knowledge of user behaviour.

B3.3.5 Light commercial vehicles

Emissions from light commercial vehicles are treated separately in Part B4 of this Report.

B3.4 Development of new models

For hot exhaust emissions four different types of model were developed in ARTEMIS:

- Instantaneous emission models.
- A kinematic regression model.
- A traffic situation model.
- Average speed models.

The development of these models is discussed below.

B3.4.1 Instantaneous emission models

There are basically two types of emissions and fuel consumption model - one based on bag measurements and the other based on instantaneous measurements. The bag measurement procedure involves drawing the entire content of the exhaust into a constant volume sampling (CVS) system, where it is diluted with fresh air and, afterwards, a representative sample is put into bags. The analysis of the bags gives a single overall value for each pollutant, representing the total mass of emission produced over the driving cycle. In an instantaneous (or 'modal') model, the emissions and other vehicle-related data (vehicle speed, engine speed, *etc*.) are collected at a high time resolution (one to ten samples per second). When integrated over the driving cycle, the instantaneous emissions data should be equivalent to the bag results.

Emission models based on bag values give results for the driving pattern similar to the one used to fill the bag. If the driving behaviour changes, new measurements with comparable driving patterns have to be performed. To account for the additional effects of, say, vehicle load, road gradient or gearshift strategy, bag-based models include correction functions. However, these correction functions are based on small numbers of measurements on few vehicles, which may not be representative of the emissions behaviour. Moreover, the combination of these correction factors (*i.e.* when a vehicle drives uphill with a full load) can be extremely misleading.

Instantaneous emission modelling maps the emissions at a given time to their generating 'engine state', like vehicle speed, engine speed, torque, *etc*. This makes it possible to input new, unmeasured driving patterns into the model, and to calculate the associated emission factors without further measurement. Thus, emission factors for a large number of driving situations can be determined from a small number of measurements.

Early examples of instantaneous emission models for light-duty vehicles can be found in Joumard *et al.* (1995a) and Barth *et al.* (1996), but their accuracy was questionable (Sturm *et al.*, 1998). Two new models were built within ARTEMIS at EMPA and TUG (PHEM) (Zallinger *et al.*, 2005a).

EMPA model

The approach developed by EMPA for characterising light-duty vehicle modal events involved the establishment of an emission matrix based on engine speed ***n*** (in rpm), brake mean effective pressure ***bmep*** (in bar) and the derivative of manifold pressure $\dot{p}$ as a dynamic variable able to express the transient generation of emissions (Ajtay and Weilenmann, 2004a; Ajtay, 2005). This matrix provided the instantaneous emissions and fuel consumption for different combinations of instantaneous values of ***n***, ***bmep*** and $\dot{p}$. The brake mean effective pressure could be considered as 'scaled' engine torque size, since:

$$bmep = \frac{T_e 4\pi}{V_d}$$ (Equation B3-20)

Where V_d = displacement volume of the engine
T_e = engine torque
4 = number of strokes per engine cycle

Thus, the brake mean effective pressure is the same for different engines when running at similar operating points (unlike torque), and is useful for comparing different cars.

For the model development, data from three pre-Euro I petrol cars, ten petrol cars with a three way catalyst (Euro III), and seven Euro II diesel cars were available. Each car was been measured according to a programme that included 16 different real-world driving cycles. During the measurements, the emission signals (CO, CO_2, HC, NO_x) and all other engine-related signals (vehicle speed, engine speed, vehicle torque, *etc*.) were logged at a frequency of 10 Hz.

For each cell of the ***bmep*** x ***n*** x $\dot{p}$ matrix, the emission or fuel consumption rate ***e*** was averaged. Instantaneous emissions and fuel consumption were then estimated by interpolating values from the corresponding combinations of ***bmep***, n, and $\dot{p}$:

$$e\,[g/s] = f(bmep, n, \dot{p})$$ (Equation B3-21)

Such ***bmep*** x ***n*** x $\dot{p}$ maps were constructed for fuel consumption and the emissions using the same time basis as for the input signals. The basic outputs of this model were the instantaneous fuel consumption and emissions at their location of formation (catalyst-out or engine-out). For this purpose, the emission signal after the catalyst was reconstructed from the emission signal measured after the CVS (Weilenmann *et al.*, 2002, 2003a; Ajtay *et al.*, 2004, 2005; Ajtay and Weilenmann, 2004b; Le Anh *et al.*, 2005a, 2005b), so that emissions at their location of formation could be properly related to the engine variables. The objective was not to have a good prediction quality at each time step, but only that the integrated emission result over a cycle of several minutes duration was reasonably accurate.

The model was validated firstly by a cross-validation method, and secondly by comparing measured and calculated emissions for new tested cars. The results indicated a very good agreement for both the integrated results and the instantaneous comparison. The model showed an excellent prediction quality for the engine-out emissions of petrol vehicles (**Figure B3-18**). For diesel vehicles, the quality of the simulation was very good for CO_2 and NO_x, and satisfactory for HC and CO.

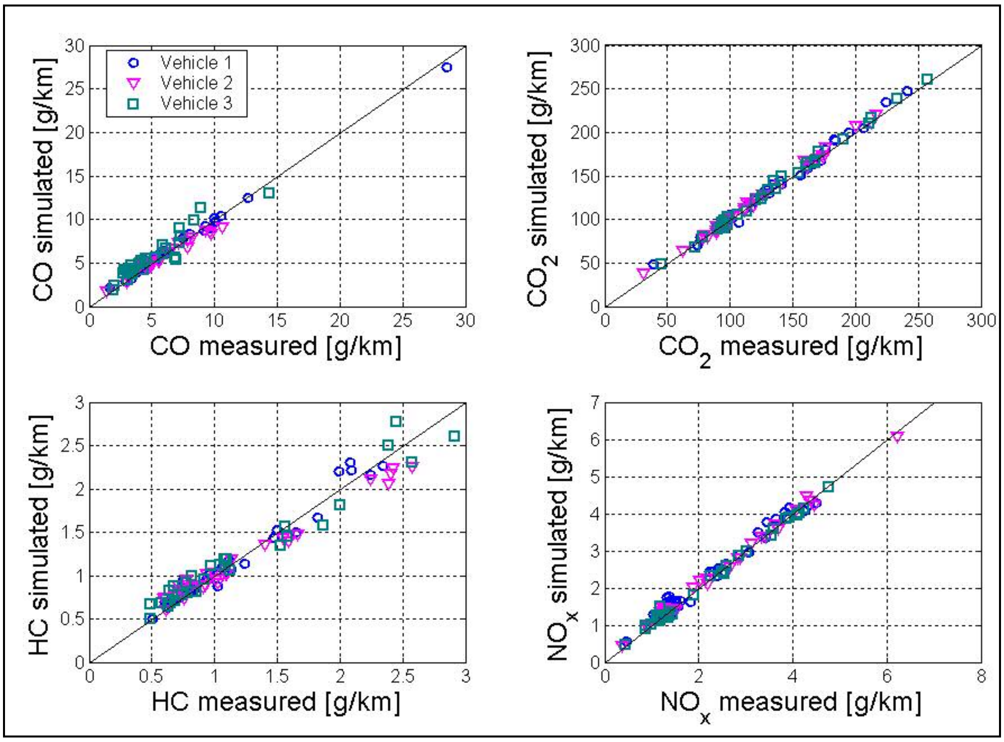

Figure B3-18: Simulation quality for the engine-out emission factors of the three Euro III petrol vehicles using the EMPA instantaneous emission model. Each point represents a separate driving pattern.

PHEM (passenger cars)

The TUG approach involved the definition of an emission matrix based on engine speed ***n*** (in rpm) and effective engine power ***P*** (in kW) (Zallinger *et al.*, 2005a and 2005b). As in the EMPA model, the measured instantaneous emissions were corrected from the time delay of the analyser and the variable transport time in the measurement system (Le Anh *et al.*, 2005a). Then, based on the driving resistances and the transmission losses, the engine power ***P*** was simulated on a second-by- second basis according to the equation:

$$P = P_{rolling\ resis\tan ce} + P_{air\ resis\tan ce} + P_{acceleration} + P_{road\ gradient} + P_{transmission\ losses} + P_{auxiliaries} \qquad \text{(Equation B3-22)}$$

The formulae used are described in Part B5 of this Report, since the simulation routine was similar for cars and HDVs. With the instantaneous emission model, it is possible to simulate the emission factors for 'average' pre-Euro I to Euro IV diesel and petrol cars, as well as for specific individual cars.

The validation of the model for the simulation of different road gradients was reported by Zallinger and Hausberger (2004). For the validation, the average emissions measured over 12 Handbook driving cycles for five Euro II diesel and six Euro III petrol cars were compared with the simulation results for an average Euro II diesel car and an average Euro III petrol car. The engine maps for the average cars were created using the instantaneous measurements on eight diesel cars over the ARTEMIS driving cycle and six Euro III petrol cars over the Handbook driving cycles. From the engine maps of the single cars, the average emission rate for each map point was calculated to establish the average engine map for a vehicle category. In the simulation the average vehicle characteristics (mass, drag coefficient, *etc*) were used together with the average engine map. The results for the average diesel car showed a high accuracy for fuel consumption and NO_x, and adequate results for HC, CO and PM mass, even without the application of transient correction functions. Similar results were obtained for all single diesel cars. Since the engine maps were created from a completely different set of measurements (ARTEMIS) than the simulated cycles (Handbook) in terms of gear shift rules and acceleration values, the model for diesel cars appeared to be very reliable. The results for the average petrol car showed that for fuel consumption, CO and HC the accuracy of the simulation was good. NO_x was overestimated, but the reasons for this are were not clear, and the very low absolute values have to be taken into consideration when looking at the deviation between measurement and simulation.

Conclusions

The 'static' instantaneous emission models developed by both EMPA and TUG gave accurate results for pre-Euro I petrol and diesel vehicles. However, the prediction quality was not satisfactory for modern three-way catalyst vehicles. Since the hot emissions of modern catalyst cars are very low, short peaks mainly occur during transient loads and dominate the overall emission. To predict such emission peaks, the models were extended by the inclusion of transient corrections. The EMPA model used as a dynamic variable the derivative of the manifold pressure, which resulted in an accurate prediction of engine-out emissions. A catalyst model is being considered which has, as a basic approach, the modelling of the oxygen storage and release phenomenon. The PHEM model uses empirical transient correction functions based on several transient parameters, such as derivatives of engine power and engine speed over different time spans.

Considering fleets (groups) of vehicles, the quality of the models improves compared with the individual vehicle. This proves that the errors for the individual vehicle models are random and not systematic. Thus, the two instantaneous emission models, although rather complex to develop, are able to predict aspects like load, gradient or different gear-shift scenarios without introducing any ambiguous correction functions as in the case of bag-based models. Indeed, PHEM was used to assess the correction factors for road gradient and vehicle load (see Section B3.3.1).

B3.4.2 Kinematic regression model

The development of the kinematic model was presented in detail by Della Ragione *et al.* (2003), Rapone *et al.* (2003) and Rapone *et al.* (2005a to 2005e, 2006a, 2006b). The general aims of this work were:

(i) To analyse the ARTEMIS emission data for different combinations of vehicle type and driving behaviour.

(ii) To develop a model capable of predicting emissions for short trips as a function of the kinematic parameters relating to a driving pattern, as obtained, for example, from either on-road measurements or traffic micro-simulation models.

Method

The full ARTEMIS database of emission factors (see Section B3.5) was used in the work, and therefore a large number of driving cycles and sub-cycles were included. The vehicles in database were also grouped by emission standard (Euro I to IV) and engine capacity (1.2-1.4 litres, 1.4-2.0 litres and > 2.0 litres) where possible.

Firstly, an analysis of variance was carried out on the whole set of data to examine the effects of driving cycle, emission standard and engine size on emissions, and to estimate the amount of emission variability contributed by each factor. The effects of the driving cycle on emissions were then estimated as a function of various kinematic parameters. To this end, an analytical model was developed using a consistent set of kinematic parameters and a multivariate regression method based on principal components (Rapone, 2005).

The unit mass emissions factors of CO, HC, NO_x, CO_2 and PM (expressed in g/km) were used. A log-transform of these emissions was applied in the regression model, firstly because in some cases the emissions were close to zero with a large coefficient of variation, and secondly because the emission factors were distributed according to a log-normal distribution. Moreover, this transform gave a better explanation of non-linear relationships with explicative variables.

In the regression model the explicative variables which were used to characterise the kinematics of driving cycles were separated into the following two blocks:

- A block 1 of 7 variables describing dynamics, plus idling time to consider emissions when stationary, and the reciprocal of driven distance to take into account that the response variables were unit emissions:

  mv average running speed (v>0)
  mv^2 average of the square speed(v>0)
  mv^3 average of the cube speed (v>0)
  t_{idle} idling duration (v=0)
  $t_{running}$ duration at running speed (driving speed without stops)
  mva average product of instantaneous speed and acceleration (with $v(t)$>0 and $a(t)$>0)
  $1/d$ reciprocal of the trip length d

- A block 2 of 42 variables, summarising kinematic acceleration events, which especially affect CO, HC and NO_x emissions (André, 2004):

  $f_{va}(v, a)$ Two-dimensional distribution of the instantaneous speed v and acceleration a with six speed classes limited by 0, 20, 40, 60, 80 and 100 km/h, and seven acceleration classes limited by -1.4, -0.6, -0.2, 0.2, 0.6 and 1.0 ms^{-2}.

A detailed multi-step outlier analysis was performed. Because of the high number of variables and co-linearity problems, the partial-least-squares (PLS) regression method was used in the model (Tenenhaus, 1998; Westerhuis *et al.*, 1998). According to the multi-block PLS approach, a regression model was fitted to the two blocks of variables separately. As a consequence, a base model 1 was defined for block 1, and a model 2 was calculated for block 2. Finally an 'upper level' model (model 3) was calculated using the pooled blocks of variables 1 and 2. Emission factors were then calculated using each of the three models, according to the best fit.

In addition, a model which considered individual vehicle effect on emissions was been fitted to data to outline individual emission trends and to determine eventual outliers. The effects of individual vehicles were estimated by building a further model (1D), which was an extension of model 1 by including – in addition to the 7 quantitative variables - a set of dummy variables indicating respectively the absence or presence of a specific vehicle. The emission factors obtained in this way therefore included vehicle effects as random effects not explained by the model.

Finally, emission factors were calculated for all vehicles in each category. Vehicles were also divided into two sets: normal emitters and high emitters.

Results

For each vehicle category (fuel, engine capacity, emission standard) the final kinematic model consists of the following:

- A model for low emitters.
- A model for high emitters.
- A model for all vehicles.
- A model for all vehicles with dummy quantifying the relative effect of each vehicle on the overall mean.

For the first three of the above models, and for a given pollutant and vehicle class, three emission factor models were produced:

- Model 1, based upon 7 kinematic parameters.
- Model 2, based upon 42 parameters.
- Model 3, based upon 49 parameters.

Figure B3-19 illustrates the measured emissions of CO_2, and emissions calculated with the three models, to show the ability of the models to follow the data trend and the comparison with a simple average speed regression model. Model 1 is the easiest to understand, because the inputs are average parameters, but it is the worst model in terms of goodness of fit. Model 2 performs better and is, for most cases, very close to the Model 3, which is the most representative.

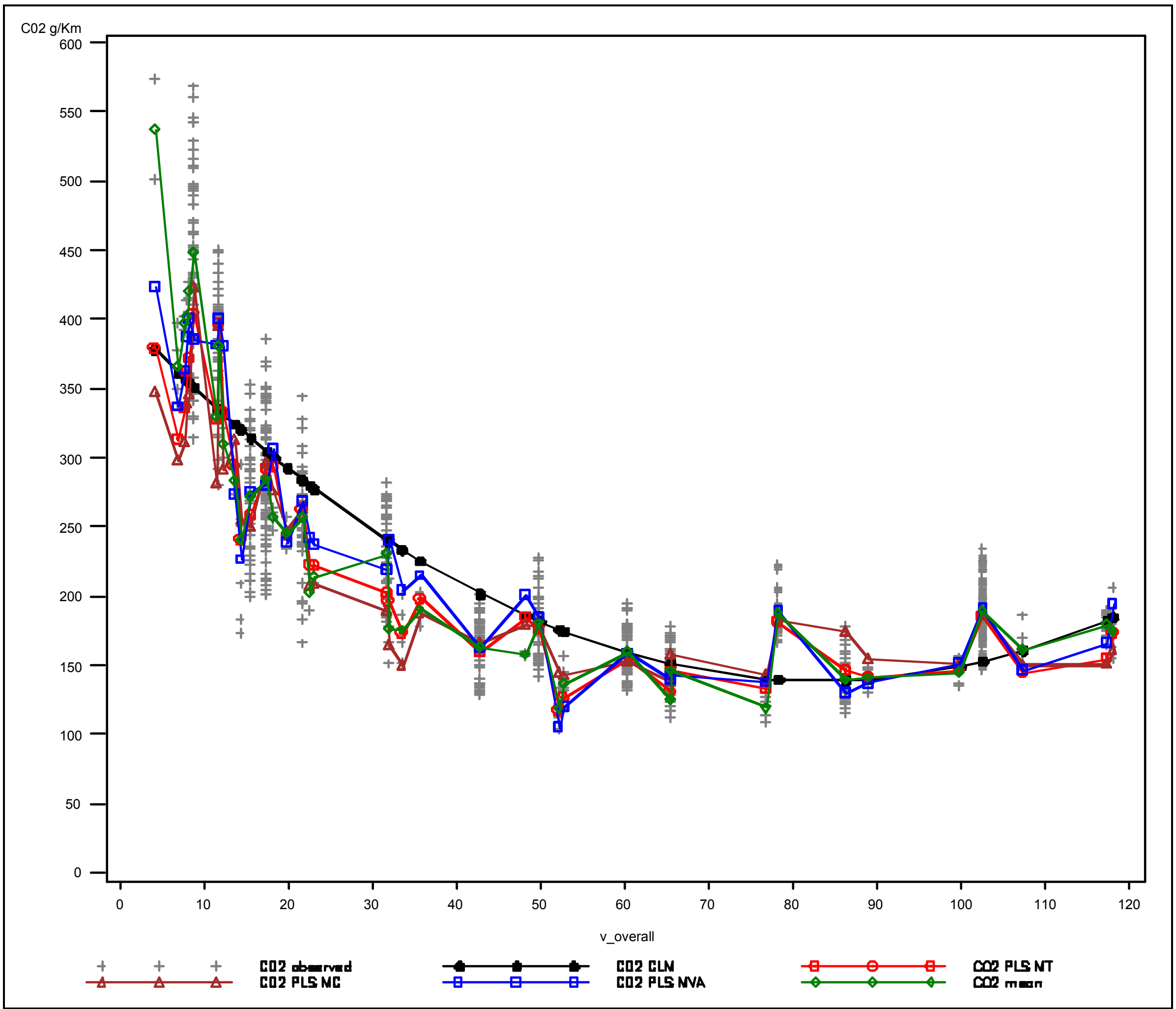

Figure B3-19: Comparison of measured and calculated emissions of CO_2 [g/km] for the kinematic regression Model 1 (PLS MG, dark red), Model 2 (PLS MVA, blue) and Model 3 (PLS MT, red), and for a general linear model (GLM, black) with the mean measured emission (mean, green) versus the driving cycle mean speed.

B3.4.3 Traffic situation model

The development of the traffic situation scheme was described in Section B2.5, and the derivation of the corresponding emission factors was introduced in Section B3.2.3. The allocation of emission factors to traffic situations is described in more detail here. After designing the 15 Reference Test Patterns, it was necessary to process the emission data to allocate an emission factor to each one. Two different approaches were developed, and these are summarised below.

Firstly, the measured emission data were corrected according to the vehicle mileage, gearshift behaviour, ambient temperature and humidity (see Section B3.2.8), in order to standardise the data and produce a 'harmonised' database. The emission data, and later the emission models, were standardised as follows:

- vehicle mileage = 50,000 km
- ambient air temperature = 23°C
- ambient air humidity = 10.71 g H_2O/kg dry air

As a second step, two models for deriving the emission factors for the Reference Test Patterns were developed.

Model 1

Model 1 took into account a subset of the emission database (Kljun and Keller 2006). Amongst the 25 cycles or sub-cycles representing the 15 RTPs, 15 cycles were considered (the 14 ARTEMIS sub-cycles and one other cycle), together with another sub-cycle which was not a Reference Test Cycle. This was conducted so that a consistent vehicle sample was used for all RTPs as far as possible. With this condition, the number of available measurements was significantly reduced - only Euro II and Euro III vehicles could be included (*i.e.* 1,500 vehicle tests or 94 hours of measurements).

For vehicle categories other than Euro II and Euro III where no coherent data (*i.e.* same vehicle sample for the selected driving cycles) were available, the emission factors were derived from those of Euro II and Euro III by applying conversion ratios. These conversion ratios were computed using COPERT III (Ntziachristos and Samaras, 2000a and 2000b), the Handbook of Emission Factors (Keller, 2004), and the assumptions for new (not yet measured) vehicle technologies provided in Section B3.4.4.

Model 2

Model 1 was found to have a number of drawbacks:

(i) Loss of representativity due to the low number of cars considered.
(ii) The reduced confidence in the emission data measured over short sub-cycles rather than entire cycles.
(iii) Loss of representativity of the driving cycles used compared to the RTCs.
(iv) The questionable validity of the conversion ratios based on emissions functions established in a different context.

As a result, Model 2 was developed using the whole emission database (André *et al.*, 2006a). A list of driving cycles was determined for each RTP in order to compute the reference emission factors. Around 20,000 measurements were analysed, and 10,900 consistent measurements, corresponding to 1,400 hours of data, were retained. This enabled the computation of emission factors for diesel and petrol cars from pre-Euro I to Euro IV. An example of the approach used is given in **Figure B3-20**. The amount of data processed was therefore much larger than for Model 1.

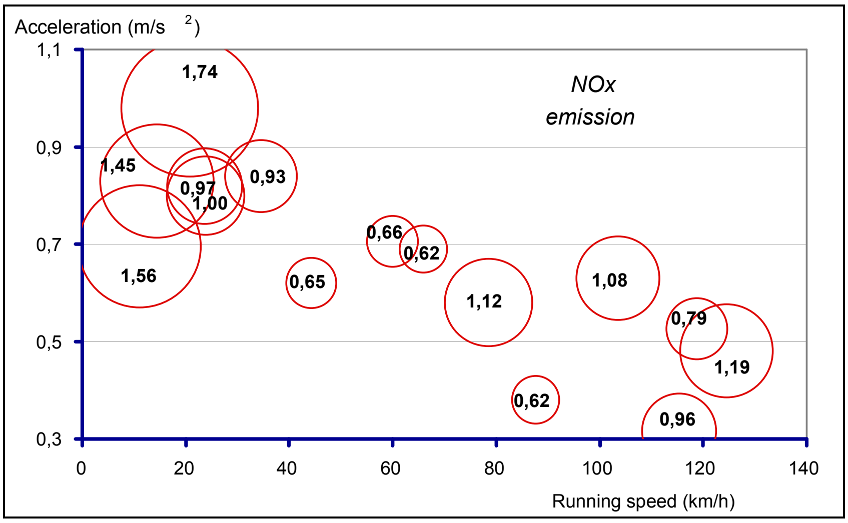

Figure B3-20: Variation of the pollutant emissions (NO_x, Euro III diesel) according to the 15 reference test patterns.

The measured emission data were not, however, corrected according to the vehicle mileage, gearshift behaviour, ambient temperature and humidity. Furthermore, weighing factors – as initially envisaged and according to the quality of the cycles and to the number of data - were not rigorously implemented through the above cycle selection process.

The reference emission factors for the RTPs are provided in **Tables B3-42** and **B3-43**. These values are allocated to specific traffic situations within the ARTEMIS model (André *et al.*, 2006c). The CO_2 emission factors can also be expressed according to the engine size (see Joumard *et al.,* 2007). This dataset was then used for further analyses to establish the various emissions functions and factors according to the other emission estimation approaches (*e.g.* average speed).

The computation of the emission factor per driving pattern is a robust approach, as it relies on contrasting driving conditions and considers the driving cycles according to their quality. Furthermore, the mapping of driving cycles provides a good representation of driving conditions in relation to average speed and acceleration (*i.e.* the dynamics of the traffic condition). Indeed, for certain pollutants (NO_x and CO_2) and vehicle categories, two classes of driving could be identified along the speed scale (*i.e.* stable or normal driving with low acceleration and stop frequencies on one hand, and unsteady driving on the other hand, as previously shown in **Figure B3-4**.

Table B3-42: Emissions according for the Reference Test Patterns (CO and HC).

Pollutant and reference test pattern	Av. speed km/h	Diesel cars					Petrol cars				
		pre-Euro I	Euro I	Euro II	Euro III	Euro IV	pre-Euro I	Euro I	Euro II	Euro III	Euro IV
CO [g/km]											
1 Urban dense	17	0.962	0.455	0.463	0.210	0.342	21.873	4.348	1.616	0.747	0.151
2 Congested urban, low speeds	12	0.826	0.400	0.534	0.316	0.128	26.857	2.318	2.086	0.965	0.297
3 Congested urban, stops	9	1.166	0.926	0.858	0.549	0.057	33.682	3.069	1.235	1.249	0.341
4 Free-flowing urban	22	1.081	0.535	0.430	0.225	0.076	25.612	4.746	1.686	0.776	0.255
5 Free-flow urban, unsteady	32	0.840	0.504	0.447	0.199	0.072	16.434	2.617	1.022	0.504	0.117
6 Rural	43	0.480	0.299	0.212	0.154	0.013	8.969	0.697	0.329	0.297	0.093
7 Stop and go	7	1.985	0.859	0.907	0.239	0.251	50.564	9.619	2.102	0.363	0.220
8 Main roads	88	0.444	1.640	0.071	0.017	0.001	4.191	1.683	0.447	0.371	0.236
9 Rural steady	66	0.436	0.234	0.144	0.090	0.008	6.678	0.930	0.280	0.317	0.123
10 Main roads, unsteady	79	0.414	0.265	0.124	0.034	0.003	11.199	1.652	1.087	1.212	0.858
11 Rural unsteady	58	0.633	0.234	0.148	0.055	0.005	11.039	2.265	1.461	0.785	1.382
12 Motorway, high speed	125	0.380	0.352	0.052	0.023	0.019	14.800	2.861	3.299	3.892	5.236
13 Motorway	119	0.401	0.155	0.064	0.013	0.011	16.141	1.088	2.618	3.196	0.543
14 Motorway, unsteady	104	0.399	0.292	0.076	0.016	0.013	14.569	1.343	1.034	2.875	0.681
15 Motorway, stable	115	0.705	0.400	0.082	0.012	0.010	12.028	6.265	2.158	2.011	0.348
HC [g eq. C_3H_8 /km]											
1 Urban dense	17	0.190	0.077	0.072	0.030	0.030	3.221	0.387	0.160	0.029	0.005
2 Congested urban, low speeds	12	0.137	0.069	0.114	0.072	0.024	3.327	0.511	0.226	0.035	0.006
3 Congested urban, stops	9	0.225	0.108	0.131	0.079	0.028	4.234	0.527	0.173	0.050	0.002
4 Free-flowing urban	22	0.229	0.050	0.080	0.043	0.009	2.980	0.398	0.136	0.027	0.004
5 Free-flow urban, unsteady	32	0.218	0.042	0.059	0.030	0.015	2.344	0.284	0.085	0.017	0.001
6 Rural	43	0.055	0.026	0.046	0.028	0.018	1.020	0.085	0.038	0.012	0.000
7 Stop and go	7	0.224	0.093	0.149	0.078	0.036	4.824	0.590	0.205	0.012	0.012
8 Main roads	88	0.078	0.053	0.023	0.013	0.008	0.416	0.064	0.036	0.014	0.005
9 Rural steady	66	0.045	0.018	0.033	0.021	0.013	0.769	0.065	0.032	0.013	0.003
10 Main roads, unsteady	79	0.065	0.024	0.026	0.016	0.010	1.189	0.134	0.060	0.032	0.016
11 Rural unsteady	58	0.135	0.041	0.028	0.013	0.008	1.434	0.153	0.048	0.019	0.004
12 Motorway, high speed	125	0.038	0.024	0.015	0.004	0.005	0.795	0.139	0.039	0.036	0.002
13 Motorway	119	0.036	0.024	0.017	0.006	0.007	1.071	0.072	0.034	0.085	0.017
14 Motorway, unsteady	104	0.046	0.023	0.016	0.009	0.011	1.198	0.109	0.036	0.057	0.011
15 Motorway, stable	115	0.090	0.038	0.027	0.014	0.017	0.628	0.165	0.066	0.020	0.010

Table B3-43: Emissions factors for the Reference Test Patterns (NO_x, CO_2 and PM).

Pollutant and reference test cycle	Av. speed km/h	Diesel cars					Petrol cars				
		pre-Euro I	Euro I	Euro II	Euro III	Euro IV	pre-Euro I	Euro I	Euro II	Euro III	Euro IV
NO_x [g eq. NO_2 /km]											
1 Urban dense	17	0.785	1.000	1.066	0.970	0.566	1.447	0.465	0.542	0.130	0.075
2 Congested urban, low speeds	12	1.452	1.017	1.317	1.448	0.665	1.217	0.412	0.425	0.125	0.039
3 Congested urban, stops	9	1.463	1.417	1.710	1.744	0.618	1.768	0.464	0.638	0.129	0.072
4 Free-flowing urban	22	1.887	0.813	0.895	1.004	0.339	1.388	0.231	0.368	0.100	0.045
5 Free-flow urban, unsteady	32	1.062	0.742	0.781	0.925	0.441	1.241	0.304	0.419	0.097	0.041
6 Rural	43	0.611	0.506	0.510	0.652	0.394	0.641	0.214	0.164	0.043	0.024
7 Stop and go	7	3.836	1.456	1.493	1.562	0.633	1.264	0.552	0.259	0.071	0.046
8 Main roads	88	1.089	0.724	0.479	0.616	0.373	1.249	0.355	0.191	0.044	0.020
9 Rural steady	66	0.556	0.479	0.498	0.616	0.372	1.010	0.272	0.134	0.040	0.015
10 Main roads, unsteady	79	0.690	0.599	0.841	1.119	0.677	2.041	0.394	0.344	0.095	0.021
11 Rural unsteady	58	0.938	0.581	0.656	0.664	0.401	1.413	0.378	0.318	0.079	0.071
12 Motorway, high speed	125	0.912	0.838	1.185	1.187	1.115	3.073	0.511	0.152	0.091	0.083
13 Motorway	119	0.900	0.807	0.988	0.787	0.740	2.700	0.437	0.355	0.064	0.017
14 Motorway, unsteady	104	0.677	0.661	0.884	1.077	1.012	2.220	0.403	0.300	0.067	0.008
15 Motorway, stable	115	1.386	1.056	0.757	0.957	0.899	2.016	0.623	0.327	0.047	0.024
CO_2 [g/km]											
1 Urban dense	17	236	220	235	232	205	236	237	262	264	281
2 Congested urban, low speeds	12	292	251	292	298	233	375	345	345	347	381
3 Congested urban, stops	9	372	336	362	359	219	482	372	422	415	447
4 Free-flowing urban	22	245	191	204	203	151	238	230	237	237	267
5 Free-flow urban, unsteady	32	188	191	192	187	156	205	186	195	210	235
6 Rural	43	149	131	140	146	130	153	163	166	154	156
7 Stop and go	7	432	282	335	302	269	429	453	484	370	378
8 Main roads	88	188	194	128	119	106	144	171	142	136	139
9 Rural steady	66	141	125	133	130	116	136	173	142	140	143
10 Main roads, unsteady	79	190	179	182	165	147	174	165	189	179	183
11 Rural unsteady	58	182	147	152	143	128	151	155	156	165	170
12 Motorway, high speed	125	216	209	191	171	181	197	185	195	197	190
13 Motorway	119	220	173	190	153	162	184	174	156	177	198
14 Motorway, unsteady	104	198	177	174	149	158	170	158	155	169	189
15 Motorway, stable	115	247	245	180	162	172	179	201	184	171	182
PM mass [g/km]											
1 Urban dense	17	0.114	0.090	0.092	0.044	0.041	0.151	0.004	0.002	0.006	0.002
2 Congested urban, low speeds	12	0.125	0.099	0.061	0.042	0.038	0.170	0.004	0.002	0.003	0.001
3 Congested urban, stops	9	0.098	0.078	0.051	0.051	0.038	0.170	0.004	0.002	0.003	0.001
4 Free-flowing urban	22	0.529	0.040	0.068	0.044	0.024	0.159	0.004	0.002	0.001	0.001
5 Free-flow urban, unsteady	32	0.457	0.081	0.068	0.044	0.044	0.199	0.005	0.002	0.002	0.001
6 Rural	43	0.051	0.028	0.029	0.013	0.014	0.305	0.004	0.003	0.003	0.002
7 Stop and go	7	0.369	0.086	0.075	0.044	0.046	0.910	0.021	0.012	0.035	0.015
8 Main roads	88	0.165	0.091	0.045	0.036	0.039	0.305	0.004	0.005	0.002	0.001
9 Rural steady	66	0.054	0.030	0.031	0.014	0.015	0.305	0.004	0.003	0.003	0.002
10 Main roads, unsteady	79	0.119	0.066	0.068	0.030	0.033	0.305	0.004	0.003	0.003	0.002
11 Rural unsteady	58	0.394	0.066	0.068	0.030	0.033	0.305	0.004	0.003	0.003	0.002
12 Motorway, high speed	125	0.207	0.224	0.084	0.088	0.249	6.634	0.026	0.014	0.009	0.006
13 Motorway	119	0.096	0.088	0.087	0.037	0.105	0.537	0.002	0.006	0.004	0.002
14 Motorway, unsteady	104	0.142	0.088	0.084	0.037	0.105	2.702	0.011	0.006	0.004	0.002
15 Motorway, stable	115	0.283	0.176	0.067	0.049	0.139	4.549	0.018	0.010	0.003	0.002

Emission factors for traffic situations

The emission mapping approach developed through the use of Reference Test Patterns is particularly appropriate for the calculation of emission factors for the different traffic situations defined in Section B2.5, as the structure enables analyses to be conducted at a relatively microscopic scale. The idea was then to link a given traffic situation as a function of the different sub-cycles for which emissions were known (André *et al*., 2006c).

The representative driving patterns for the traffic situations were analysed, together with the reference test cycles, in terms of their speed and acceleration distributions. Binary correspondences analysis was used to transform the time distribution into factorial coordinates, and to then calculate distances between a driving pattern (*i.e* for a traffic situation) and the test cycles. This was exactly the same method that was used to characterise driving patterns in the development the ARTEMIS driving cycles, and also to determine the emission factors for the RTPs in Model 2 described above.

The distances between a driving pattern for a traffic situation and the test cycles enabled the closest test cycles to be identified, and each traffic situation to be described as a linear combination of the RTPs, in proportion to their proximity (in term of kinematics) to these RTPs. A set of weighting coefficients was then determined for each traffic situation according to the 15 RTPs, as shown in **Tables B3-44** and **B3-45**.

Therefore, the emission factors for hundreds of traffic situations were computed by linear combination of the reference emissions for the closest RTPs, as defined in Model 2. These emission factors are illustrated in **Figure B3-21** for some vehicle classes and for the four main traffic conditions (described in **Figure B2-1)**.

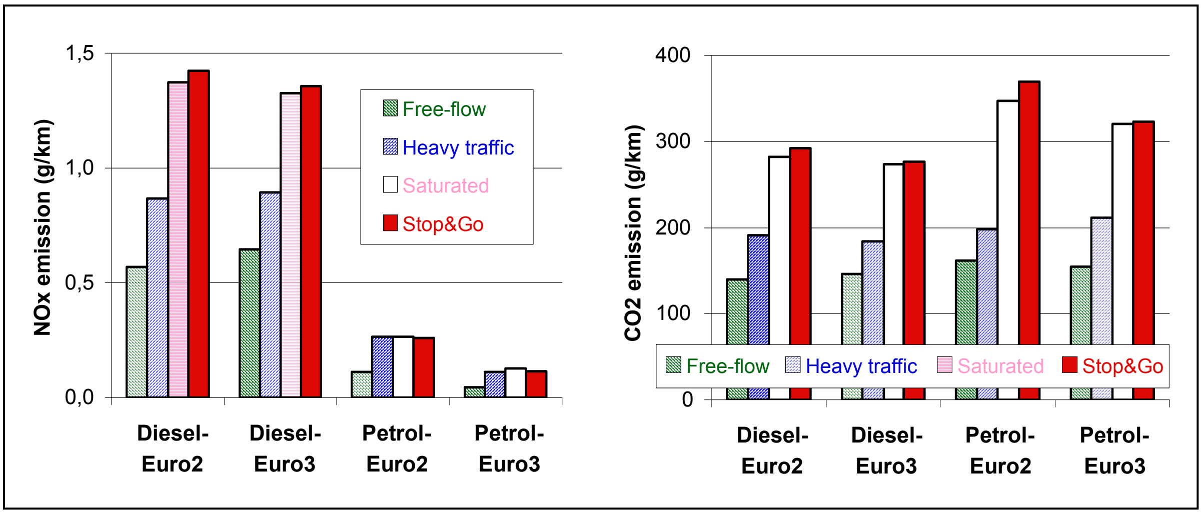

Figure B3-21: Traffic situation approach illustration: NO_x and CO_2 emissions of cars have been estimated for an urban trunk road (speed limit: 50 km/h), at different traffic conditions, according to dedicated speed curves.

Emission factors of macro traffic situations

The four macro traffic situations (urban, rural, motorway, European) are based on the weighting of the ARTEMIS cycles in the traffic, and were part of the design of these driving cycles (André, 2004a). They can be expressed according to the three ARTEMIS cycles or according to all ARTEMIS sub-cycles. As each of the ARTEMIS cycles and sub-cycles is also a specific traffic situation in its own right, the macro traffic situations can be expressed according to these traffic situations. Their weightings in relation to the traffic situations 1002 to 1024 are shown in **Table B3-44**). The macro traffic situations are termed 'composite' when they are expressed according to the ARTEMIS sub-cycles.

As all the traffic situations are expressed according the Reference Test Patterns, the macro traffic situations, including the composite ones, can be expressed according to the RTPs (**Table B3-45**). However, the composite macro traffic situations are not useful for calculating hot emission factors; the normal macro traffic situations are simpler as they are expressed according to the main ARTEMIS cycles. They are useful when emission factors are expressed according to the average speed and are not linear functions of the speed as, for instance, in the case of cold-start emissions (see Section B7), or for the LDVs (see Section B4). The inclusion of the composite macro traffic situations rather than the non-composite macro situations should not greatly improve the accuracy of the corresponding emission factors.

Table B3-44: Descriptions of the rural traffic situations for which speed data were available.

ID speed curve	Area	Road Category	Speed limit (km/h)	Gradient, sinuosity	Traffic condition	Identification
40	Rural	national/regional motorway	130	Flat, non-sinuous	Free-flow	110131
87	Rural	national/regional motorway	150	Flat, non-sinuous	Free-flow	110141
88	Rural	national/regional motorway	150	Flat, non-sinuous	Free-flow	110141
89	Rural	national/regional motorway	150	Flat, non-sinuous	Free-flow	110141
84	Rural	Semi-motorway	90	Flat, non-sinuous	Free-flow	112091
75	Rural	Semi-motorway	90	Flat, non-sinuous	Heavy traffic	112092
77	Rural	Semi-motorway	90	Flat, non-sinuous	Saturated	112093
74	Rural	Semi-motorway	110	Flat, non-sinuous	Free-flow	112111
67	Rural	Semi-motorway	110	Flat, non-sinuous	Heavy traffic	112112
68	Rural	Semi-motorway	110	Flat, non-sinuous	Saturated	112113
43	Rural	national/regional trunk road	70	Flat, non-sinuous	Free-flow	120071
41	Rural	national/regional trunk road	90	Flat, non-sinuous	Free-flow	120091
51	Rural	national/regional trunk road	90	Hilly, sinuous	Free-flow	120091
52	Rural	national/regional trunk road	90	Hilly, sinuous	Free-flow	120091
42	Rural	national/regional trunk road	90	Hilly, sinuous	Free-flow	120091
46	Rural	distributor, inter village road	50	Flat, non-sinuous	Free-flow	130051
45	Rural	distributor, inter village road	70	Mountainous, sinuous	Free-flow	130071
53	Rural	distributor, inter village road	90	Mountainous, sinuous	Free-flow	130091
54	Rural	distributor, inter village road	90	Mountainous, sinuous	Free-flow	130091
55	Rural	distributor, inter village road	90	Mountainous, sinuous	Free-flow	130091
56	Rural	distributor, inter village road	90	Mountainous, sinuous	Free-flow	130091
44	Rural	distributor, inter village road	90	Mountainous, sinuous	Free-flow	130091
57	Rural	distributor, inter village road	90	Mountainous, sinuous	Free-flow	130091
58	Rural	distributor, inter village road	90	Mountainous, sinuous	Free-flow	130091
59	Rural	distributor, inter village road	90	Mountainous, sinuous	Free-flow	130091
60	Rural	distributor, inter village road	90	Mountainous, sinuous	Free-flow	130091

Table B3-45: Descriptions of the urban traffic situation for which speed data were available.

ID speed curve	Area	Road Category	Speed limit (km/h)	Gradient, sinuosity	Traffic condition	Identification
2	Urban	national/regional motorway	110	Flat, non-sinuous	Free-flow	210111
3	Urban	national/regional motorway	110	Flat, non-sinuous	Heavy traffic	210112
4	Urban	national/regional motorway	110	Flat, non-sinuous	Stop and go	210114
1	Urban	national/regional motorway	130	Flat, non-sinuous	Free-flow	210131
8	Urban	City or urban motorway	80	Flat, non-sinuous	Heavy traffic	211082
7	Urban	City or urban motorway	90	Flat, non-sinuous	Free-flow	211091
5	Urban	City or urban motorway	100	Flat, non-sinuous	Free-flow	211101
6	Urban	City or urban motorway	100	Flat, non-sinuous	Heavy traffic	211102
16	Urban	City primary road, major arterial	50	Flat, non-sinuous	Free-flow	221051
17	Urban	City primary road, major arterial	50	Flat, non-sinuous	Heavy traffic	221052
18	Urban	City primary road, major arterial	50	Flat, non-sinuous	Saturated	221053
19	Urban	City primary road, major arterial	50	Flat, non-sinuous	Stop and go	221054
12	Urban	City primary road, major arterial	60	Flat, non-sinuous	Free-flow	221061
13	Urban	City primary road, major arterial	60	Flat, non-sinuous	Heavy traffic	221062
14	Urban	City primary road, major arterial	60	Flat, non-sinuous	Saturated	221063
15	Urban	City primary road, major arterial	60	Flat, non-sinuous	Stop and go	221064
9	Urban	City primary road, major arterial	80	Flat, non-sinuous	Free-flow	221081
10	Urban	City primary road, major arterial	80	Flat, non-sinuous	Heavy traffic	221082
11	Urban	City primary road, major arterial	80	Flat, non-sinuous	Stop and go	221084
28	Urban	Districts distributor, inter district road	50	Flat, non-sinuous	Free-flow	230051
29	Urban	Districts distributor, inter district road	50	Flat, non-sinuous	Heavy traffic	230052
30	Urban	Districts distributor, inter district road	50	Flat, non-sinuous	Saturated	230053
31	Urban	Districts distributor, inter district road	50	Flat, non-sinuous	Stop and go	230054
24	Urban	Districts distributor, inter district road	60	Flat, non-sinuous	Free-flow	230061
25	Urban	Districts distributor, inter district road	60	Flat, non-sinuous	Heavy traffic	230062
26	Urban	Districts distributor, inter district road	60	Flat, non-sinuous	Saturated	230063
27	Urban	Districts distributor, inter district road	60	Flat, non-sinuous	Stop and go	230064
20	Urban	Districts distributor, inter district road	70	Flat, non-sinuous	Free-flow	230071
21	Urban	Districts distributor, inter district road	70	Flat, non-sinuous	Heavy traffic	230072
22	Urban	Districts distributor, inter district road	70	Flat, non-sinuous	Saturated	230073
23	Urban	Districts distributor, inter district road	70	Flat, non-sinuous	Stop and go	230074
32	Urban	Local distributor	50	Flat, non-sinuous	Free-flow	240051
47	Urban	Local distributor	50	Flat, non-sinuous	Saturated	240053
33	Urban	Local distributor	50	Flat, non-sinuous	Stop and go	240054
38	Urban	Local access	30	Flat, non-sinuous	Free-flow	250031
50	Urban	Local access	30	Flat, non-sinuous	Saturated	250033
39	Urban	Local access	30	Flat, non-sinuous	Stop and go	250034
36	Urban	Local access	40	Flat, non-sinuous	Free-flow	250041
49	Urban	Local access	40	Flat, non-sinuous	Saturated	250043
37	Urban	Local access	40	Flat, non-sinuous	Stop and go	250044
34	Urban	Local access	50	Flat, non-sinuous	Free-flow	250051
48	Urban	Local access	50	Flat, non-sinuous	Saturated	250053
35	Urban	Local access	50	Flat, non-sinuous	Stop and go	250054

Table B3-46: Description of the traffic situation corresponding to the ARTEMIS driving cycles or sub-cycles, and weighting factors of macro traffic situations according to these cycles.

ID speed curve	Name of the cycle or sub-cycle	Area	Road Category	Speed limit (km/h)	Gradient, sinuosity	Traffic condition	absolute weight (André, 2004a)			
							European	European composite	European 130	European 130 composite
1002	TS_ARTEMIS.urban	Urban	Districts distributor, inter district road	50	Flat, non-sinuous	Heavy traffic	0.292		0.292	
1003	TS_ARTEMIS.urban_1	Urban	Districts distributor, inter district road	50	Flat, non-sinuous	Saturated		0.059		0.059
1004	TS_ARTEMIS.urban_2	Urban	Districts distributor, inter district road	50	Flat, non-sinuous	Saturated		0.122		0.122
1005	TS_ARTEMIS.urban_3	Urban	Districts distributor, inter district road	50	Flat, non-sinuous	Stop and go		0.037		0.037
1006	TS_ARTEMIS.urban_4	Urban	Districts distributor, inter district road	50	Flat, non-sinuous	Stop and go		0.024		0.024
1007	TS_ARTEMIS.urban_5	Urban	Districts distributor, inter district road	50	Flat, non-sinuous	Heavy traffic		0.051		0.051
1009	TS_ARTEMIS.road	Rural	distributor, inter village road	90	Flat, non-sinuous	Heavy traffic	0.449		0.449	
1010	TS_ARTEMIS.road_1	Rural	distributor, inter village road	90	Flat, non-sinuous	Heavy traffic		0.108		0.108
1011	TS_ARTEMIS.road_2	Rural	distributor, inter village road	90	Flat, non-sinuous	Heavy traffic		0.072		0.072
1012	TS_ARTEMIS.road_3	Rural	distributor, inter village road	90	Flat, non-sinuous	Heavy traffic		0.088		0.088
1013	TS_ARTEMIS.road_4	Rural	distributor, inter village road	90	Flat, non-sinuous	Heavy traffic		0.118		0.118
1014	TS_ARTEMIS.road_5	Rural	national/regional trunk road	90	Flat, non-sinuous	Heavy traffic		0.062		0.062
1016	TS_ARTEMIS.motorway	Rural	national/regional motorway	130	Flat, non-sinuous	Heavy traffic	0.259			
1017	TS_ARTEMIS.motorway_1	Rural	national/regional motorway	130	Flat, non-sinuous	Heavy traffic		0.093		0.095
1018	TS_ARTEMIS.motorway_2	Rural	national/regional motorway	130	Flat, non-sinuous	Heavy traffic		0.060		0.063
1019	TS_ARTEMIS.motorway_3	Rural	national/regional motorway	130	Flat, non-sinuous	Heavy traffic		0.062		
1020	TS_ARTEMIS.motorway_4	Rural	national/regional motorway	130	Flat, non-sinuous	Heavy traffic		0.044		
1022	TS_ARTEMIS.motorway130	Rural	national/regional motorway	130	Flat, non-sinuous	Heavy traffic			0.259	
1023	TS_ARTEMIS.motorway130_3	Rural	national/regional motorway	130	Flat, non-sinuous	Heavy traffic				0.061
1024	TS_ARTEMIS.motorway130_4	Rural	national/regional motorway	130	Flat, non-sinuous	Heavy traffic				0.040

Table B3-47: Weighting coefficients of the Reference Test Patterns for each of the 69 traffic situation for which speed data are available, and for the 19 additional traffic situations corresponding to each of the ARTEMIS driving cycles or sub-cycles, for the emission computation. The traffic situations 1002, 1009 and 1016 are macro traffic situations (in **bold**) resp. for urban, rural and motorway situations. They are composed of one or two Reference test patterns. A last traffic situation is the most macroscopic situation corresponding to the European traffic situation. Alternative macro traffic situations are composite ones (in ***italics***).

ID speed curve	Identification	Number of coefficients	Reference test patterns														
			1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
			Urban, Dense	Urban, Congested, low speeds	Urban, Congested, stops	Urban, Free-flowing	Urban, Free-flow, unsteady	Rural, Low speed	Urban, Stop&go	Rural, Main roads	Rural, Steady	Rural, Main roads, unsteady	Rural, Unsteady	Motorway, High speed	Motorway,	Motorway, Unsteady	Motorway, Stable
40	110131	1	0	0	0	0	0	0	0	0	0	0	0	0	1.00	0	0
87	110141	1	0	0	0	0	0	0	0	0	0	0	0	1.00	0	0	0
88	110141	1	0	0	0	0	0	0	0	0	0	0	0	1.00	0	0	0
89	110141	1	0	0	0	0	0	0	0	0	0	0	0	1.00	0	0	0
84	112091	1	0	0	0	0	0	0	0	1.00	0	0	0	0	0	0	0
75	112092	2	0	0	0	0	0	0	0	0.84	0	0	0.16	0	0	0	0
77	112093	2	0	0	0	0	0	0	0	0.68	0	0	0.32	0	0	0	0
74	112111	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1.00
67	112112	3	0	0	0	0	0	0	0	0	0	0.11	0.11	0	0	0	0.79
68	112113	4	0	0	0	0	0	0	0	0.18	0	0.19	0	0	0	0.27	0.37
43	120071	1	0	0	0	0	0	0	0	0	1.00	0	0	0	0	0	0
41	120091	2	0	0	0	0	0	0	0	0.75	0	0	0.25	0	0	0	0
51	120091	2	0	0	0	0	0	0	0	0	0	0.34	0.66	0	0	0	0
52	120091	2	0	0	0	0	0	0	0	0	0.25	0	0.75	0	0	0	0
42	120091	2	0	0	0	0	0	0	0	0	0.60	0	0.40	0	0	0	0
46	130051	1	0	0	0	0	0	1.00	0	0	0	0	0	0	0	0	0
45	130071	2	0	0	0	0	0	0	0	0	0.20	0	0.80	0	0	0	0
53	130091	2	0	0	0	0	0.42	0	0	0	0	0	0.58	0	0	0	0
54	130091	2	0	0	0	0	0.39	0	0	0	0	0	0.61	0	0	0	0
55	130091	1	0	0	0	0	0	0	0	0	0	0	1.00	0	0	0	0
56	130091	2	0	0	0	0	0.17	0	0	0	0	0	0.83	0	0	0	0
44	130091	1	0	0	0	0	0	0	0	1.00	0	0	0	0	0	0	0
57	130091	2	0	0	0	0	0	0	0	0	0.18	0	0.82	0	0	0	0
58	130091	2	0	0	0	0	0	0	0	0	0.78	0	0.22	0	0	0	0
59	130091	2	0	0	0	0	0	0.42	0	0	0	0	0.58	0	0	0	0
60	130091	2	0	0	0	0	0	0	0	0	0.13	0	0.87	0	0	0	0

Table B3-47 continued.

ID speed curve	Identification	Number of coefficients	Reference test patterns: 1 Urban, Dense	2 Urban, Congested, low speeds	3 Urban, Congested, stops	4 Urban, Free-flowing	5 Urban, Free-flow, unsteady	6 Rural, Low speed	7 Urban, Stop&go	8 Rural, Main roads	9 Rural, Steady	10 Rural, Main roads, unsteady	11 Rural, Unsteady	12 Motorway, High speed	13 Motorway,	14 Motorway, Unsteady	15 Motorway, Stable
2	210111	3	0	0	0	0	0	0	0	0.17	0	0.12	0	0	0	0	0.72
3	210112	2	0	0	0	0	0	0	0	0.52	0	0.48	0	0	0	0	0
4	210114	3	0.25	0.37	0	0.38	0	0	0	0	0	0	0	0	0	0	0
1	210131	2	0	0	0	0	0	0	0	0	0	0	0	0	0.32	0	0.68
8	211082	1	0	0	0	0	0	0	0	0	1.00	0	0	0	0	0	0
7	211091	2	0	0	0	0	0	0	0	0.47	0	0	0.53	0	0	0	0
5	211101	4	0	0	0	0	0	0	0	0.55	0	0.21	0.11	0	0	0	0.13
6	211102	3	0	0	0	0	0	0	0	0.23	0	0.50	0.27	0	0	0	0
16	221051	1	0	0	0	0	0	1.00	0	0	0	0	0	0	0	0	0
17	221052	3	0.15	0	0	0	0.66	0	0	0	0	0	0.20	0	0	0	0
18	221053	3	0.38	0.35	0	0	0	0	0.28	0	0	0	0	0	0	0	0
19	221054	3	0.44	0	0.11	0	0	0	0.45	0	0	0	0	0	0	0	0
12	221061	1	0	0	0	0	0	0	0	0	1.00	0	0	0	0	0	0
13	221062	2	0	0	0	0	0.25	0	0	0	0	0	0.75	0	0	0	0
14	221063	2	0	0	0	0.47	0.53	0	0	0	0	0	0	0	0	0	0
15	221064	2	0	0.18	0	0.82	0	0	0	0	0	0	0	0	0	0	0
9	221081	3	0	0	0	0	0	0	0	0.64	0	0.14	0.22	0	0	0	0
10	221082	2	0	0	0	0	0.14	0	0	0	0	0	0.86	0	0	0	0
11	221084	2	0	0	0	0.22	0	0	0.78	0	0	0	0	0	0	0	0
28	230051	2	0	0	0	0	0.26	0.74	0	0	0	0	0	0	0	0	0
29	230052	2	0	0	0	0	0.32	0.68	0	0	0	0	0	0	0	0	0
30	230053	3	0.45	0	0.17	0	0.38	0	0	0	0	0	0	0	0	0	0
31	230054	2	0.71	0	0.29	0	0	0	0	0	0	0	0	0	0	0	0
24	230061	2	0	0	0	0	0.26	0	0	0	0	0	0.74	0	0	0	0
25	230062	2	0	0	0	0	0.37	0.64	0	0	0	0	0	0	0	0	0
26	230063	2	0.33	0	0	0	0.68	0	0	0	0	0	0	0	0	0	0
27	230064	2	0.89	0	0.11	0	0	0	0	0	0	0	0	0	0	0	0
20	230071	2	0	0	0	0	0	0	0	0	0.70	0	0.30	0	0	0	0
21	230072	2	0	0	0	0	0	0	0	0	0.19	0	0.82	0	0	0	0
22	230073	2	0.51	0	0	0	0.49	0	0	0	0	0	0	0	0	0	0
23	230074	2	0.29	0	0.71	0	0	0	0	0	0	0	0	0	0	0	0
32	240051	2	0	0	0	0	0.79	0.21	0	0	0	0	0	0	0	0	0
47	240053	2	0.88	0	0	0.12	0	0	0	0	0	0	0	0	0	0	0
33	240054	2	0.27	0	0.73	0	0	0	0	0	0	0	0	0	0	0	0

Table B3-47 continued.

ID speed curve	Identification	Number of coefficients	1 Urban, Dense	2 Urban, Congested, low speeds	3 Urban, Congested, stops	4 Urban, Free-flowing	5 Urban, Free-flow, unsteady	6 Rural, Low speed	7 Urban, Stop&go	8 Rural, Main roads	9 Rural, Steady	10 Rural, Main roads, unsteady	11 Rural, Unsteady	12 Motorway, High speed	13 Motorway,	14 Motorway, Unsteady	15 Motorway, Stable
			Reference test patterns														
38	250031	2	0	0.43	0	0.57	0	0	0	0	0	0	0	0	0	0	0
50	250033	2	0.25	0.75	0	0	0	0	0	0	0	0	0	0	0	0	0
39	250034	2	0.57	0.43	0	0	0	0	0	0	0	0	0	0	0	0	0
36	250041	2	0	0	0	0	0.44	0.57	0	0	0	0	0	0	0	0	0
49	250043	2	0.25	0	0.75	0	0	0	0	0	0	0	0	0	0	0	0
37	250044	2	0.46	0	0.55	0	0	0	0	0	0	0	0	0	0	0	0
34	250051	3	0	0	0	0.26	0.55	0.19	0	0	0	0	0	0	0	0	0
48	250053	1	0	0	0	1.00	0	0	0	0	0	0	0	0	0	0	0
35	250054	2	0	0	0.82	0	0	0	0.18	0	0	0	0	0	0	0	0
1002	**(urban)**	**1**	**1.00**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**
1003		2	0.83	0.18	0	0	0	0	0	0	0	0	0	0	0	0	0
1004		1	0	0	0	0	1.00	0	0	0	0	0	0	0	0	0	0
1005		1	0	0	1.00	0	0	0	0	0	0	0	0	0	0	0	0
1006		1	0	1.00	0	0	0	0	0	0	0	0	0	0	0	0	0
1007		1	0	0	0	1.00	0	0	0	0	0	0	0	0	0	0	0
1009	**(rural)**	**1**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**1.00**	**0**	**0**	**0**	**0**
1010		1	0	0	0	0	0	0	0	0	0	0	1.00	0	0	0	0
1011		1	0	0	0	0	0	0	0	0	1.00	0	0	0	0	0	0
1012		1	0	0	0	0	0	1.00	0	0	0	0	0	0	0	0	0
1013		1	0	0	0	0	0	0	0	0	0	1.00	0	0	0	0	0
1014		1	0	0	0	0	0	0	0	1.00	0	0	0	0	0	0	0
1016	**(motorw.)**	**2**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0.66**	**0.34**	**0**	**0**
1017		1	0	0	0	0	0	0	0	0	0	0	0	0	1.00	0	0
1018		1	0	0	0	0	0	0	0	0	0	0	0	0	0	1.00	0
1019		1	0	0	0	0	0	0	0	0	0	0	0	1.00	0	0	0
1020		1	0	0	0	0	0	0	0	0	0	0	0	1.00	0	0	0
1022		1	0	0	0	0	0	0	0	0	0	0	0	0	1.00	0	0
1023		2	0	0	0	0	0	0	0	0	0	0	0	0	0.86	0	0.14
1024		4	0	0	0	0	0	0	0	0	0	0	0	0.15	0.39	0.19	0.27
(European)		**4**	**0.292**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0.449**	**0.171**	**0.088**	**0**	**0**
(urban composite)		***5***	***0.167***	***0.118***	***0.127***	***0.175***	***0.418***	***0***	***0***	***0***	***0***	***0***	***0***	***0***	***0***	***0***	***0***
(rural composite)		***5***	***0***	***0***	***0***	***0***	***0***	***0.196***	***0***	***0.138***	***0.160***	***0.263***	***0.241***	***0***	***0***	***0***	***0***
(motorway comp.)		***3***	***0***	***0***	***0***	***0***	***0***	***0***	***0***	***0***	***0***	***0***	***0***	***0.409***	***0.359***	***0.232***	***0***
(European comp.)		***13***	***0.049***	***0.034***	***0.037***	***0.051***	***0.122***	***0.088***	***0***	***0.062***	***0.072***	***0.118***	***0.108***	***0.106***	***0.093***	***0.060***	***0***

B3.4.4 Average-speed models

Two average-speed modelling approaches were used: (i) a first approach based on emission data clustering through speed range averages, and (ii) a second approach based on the emission factors for the 15 RTPs described earlier (see Section B3.2.3). These approaches are described below.

Design through speed range averages

Samaras and Geivanidis (2005) derived a set of average-speed emission factors for passenger cars[13] from the ARTEMIS LVEM database (see **section B3.5**). The emission factors covered CO, HC and NO_x for recent car technologies (Euro I to Euro III, and Euro IV for petrol vehicles). PM for diesel vehicles and fuel consumption were also included. Furthermore, a set of emission-reduction factors was also created in order to cover future vehicle technologies which were not included in the vehicle sample. These reduction factors were based on the emission standards for future technologies, as well as the technological improvements used to achieve the future emission and fuel consumption levels.

Only hot-start cycles were used, and all artificial cycles, or cycles used in the parametric studies, were excluded. Cycles produced as the sum of bag samples already contained in the database were also excluded in order to avoid overweighting certain data points. In addition to passenger cars, all 4 wheel drive vehicles were also included as none of them fell into the N1 category due to their low vehicle weight. All data were corrected in terms of temperature, humidity and gear-choice strategy effects, but not according to mileage, although the corrections generally had little or no effect on the level of emissions.

Due to the low number of measurements available for certain speeds, and in order to avoid overweighting of specific speed points with high numbers of measurements, emission factors were produced for speed ranges of 10 km/h. The average speed of each class produced points ranging from 5 km/h to 135 km/h. These points were then evaluated, taking into account the number of data which made up each average value. Certain points, consisting of low numbers of measurements, were eliminated in case the rest of the speed class points contained significantly higher numbers of measurements for a certain emission factor. Outliers were also eliminated.

In all cases, an equation of the following general form was used:

$$y = \frac{a + c \cdot x + e \cdot x^2}{1 + b \cdot x + d \cdot x^2} + \frac{f}{x} \qquad \text{(Equation B3-23)}$$

where

y	=	the speed dependent emission factor of fuel consumption (valid speed range = 10-130 km/h)
x	=	the average speed
a, b, c, d, e, f	=	coefficients

The emission factors were divided into more detailed categories according to engine capacity where there was an obvious effect. The emission and fuel consumption factor equations are given in **Table B3-48** and **Table B3-49**, and some of the functions are plotted in **Figures B3-23** to **B3-27** (Samaras and Geivanidis, 2005). The beneficial effect of technological improvements are obvious in the case of NO_x emissions from petrol cars and PM emissions from diesel cars. Emission factors for a hybrid petrol vehicle were also derived. The data were derived from measurements on a specific vehicle (Toyota Prius) (Fontaras *et al.*, 2006).

The characteristic of Equation B3-7 is the ability to adapt to the high slope that was observed in some cases at low and high speeds. The choice of the split of emission factors into more detailed segmentation according to engine capacity was applied in the cases where there was an obvious effect of engine capacity on the emission factor, the limiting factor being the availability of data. The equations sometimes leads to abrupt changes of behaviour outside the speed range of the data, and (*i.e.* from 5 to 135 km/h). Out of these limits, the values at the limits should be used.

[13] Including four-wheel-drive vehicles.

Table B3-48: Emission factor equations for petrol cars.

Pollutant	Emission Standard	Engine capacity	Equation	R^2	***a***	***b***	***c***	***d***	***e***	***f***
CO	Euro I	All capacities	y=(a+cx+ex^2)/(1+bx+dx^2)	0.87	11.15320657	0.128685358	-0.101503184	-0.000946631	0.000676883	
	Euro II	All capacities	y=(a+cx+ex^2)/(1+bx+dx^2)	0.97	60.5256484	3.499185561	0.152041368	-0.025212142	-0.000168436	
	Euro III	All capacities	y=(a+cx)/(1+bx+dx^2)	0.97	71.70537699	35.40666116	11.44056269	-0.248305435		
	Euro IV	All capacities	y=(a+cx)/(1+bx+dx^2)	0.93	0.136241403	-0.014097785	-0.000890931	4.98989E-05		
HC	Euro I	All capacities	y=(a+cx)/(1+bx+dx^2)	0.82	1.349382393	0.177893263	-0.006773162	-0.001272345		
	Euro II	All capacities	y=(a+cx)/(1+bx+dx^2)	0.95	4108199.712	1659966.156	-14511.33287	-10274.30718		
	Euro III	All capacities	y=(a+cx+ex^2)/(1+bx+dx^2)	0.88	0.055738489	0.036523691	-0.001102637	-0.000187725	1.25168E-05	
	Euro IV	All capacities	y=a+cx+ex^2	0.10	0.011794753		-3.47291E-05		8.83984E-07	
NO_x	Euro I	All capacities	y=a+cx+ex^2	0.86	0.524738843		-0.010032005		9.3607E-05	
	Euro II	All capacities	y=(a+cx+ex^2)/(1+bx+dx^2)	0.52	0.283553945	-0.023390896	-0.008689173	0.000443086	0.000114496	
	Euro III	All capacities	y=(a+cx+ex^2)/(1+bx+dx^2)	0.80	0.092949654	-0.012205513	-0.001490763	3.97074E-05	6.52593E-06	
	Euro IV	All capacities	y=a+cx+ex^2	0.71	0.106315088		-0.001583401		7.09522E-06	
FC	Euro I	<1.4	y=(a+cx)/(1+bx+dx^2)	0.99	190.507552	0.12906099	1.168450492	-0.000723245		
		1.4-2.0	y=(a+cx)/(1+bx+dx^2)	0.98	199.4956409	0.089245234	0.346249391	-0.00053801		
		>2.0	y=(a+cx)/(1+bx+dx^2)	0.93	230.0493812	0.069360039	-0.042598666	-0.000446338		
	Euro II	<1.4	y=(a+cx+ex^2)/(1+bx+dx^2)	0.99	207.5258849	0.106724999	-0.565372973	-0.000500018	0.014269811	
		1.4-2.0	y=(a+cx+ex^2)/(1+bx+dx^2)	0.98	346.7895261	0.216777874	2.725507153	-0.000910501	0.004281619	
		>2.0	y=(a+cx)/(1+bx+dx^2)	0.98	1539.083363	0.869030335	19.07516558	-0.003625444		
	Euro III	<1.4	y=(a+cx+ex^2)/(1+bx+dx^2)	0.99	169.5677149	0.092836318	0.418324779	-0.000451903	0.004986675	
		1.4-2.0	y=(a+cx+ex^2)/(1+bx+dx^2)	0.99	217.0507554	0.095972866	0.253496927	-0.000421365	0.009651816	
		>2.0	y=(a+cx)/(1+bx+dx^2)	0.99	253.2315995	0.090248921	0.501611867	-0.000468596		
	Euro IV	<1.4	y=(a+cx+ex^2)/(1+bx+dx^2)	0.95	136.2596257	0.026010686	-1.6475393	0.000227505	0.031222313	
		1.4-2.0	y=(a+cx+ex^2)/(1+bx+dx^2)	0.96	173.7871418	0.068499485	0.364000835	-0.000246809	0.008739103	
		>2.0	y=(a+cx)/(1+bx+dx^2)	0.98	285.0309931	0.072817643	-0.137181957	-0.000416216		

Table B3-49: Emission factor equations for diesel cars.

Pollutant	Emission Standard	Engine capacity	Equation	R^2	*a*	*b*	*c*	*d*	*e*	*f*
CO	Euro I	All capacities	y=**a**+**cx**+**ex**^2	0.94	0.995787107		-0.018772272		0.000108897	
	Euro II	All capacities	y=**a**+**cx**+**ex**^2	0.91	0.899711748		-0.017417942		8.77264E-05	
	Euro III	All capacities	y=**a**+**cx**+**ex**^2+**f**/**x**	0.95	0.168637914		-0.002924642		1.24692E-05	1.095523771
HC	Euro I	<2.0	y=(**a**+**cx**+**ex**^2)/(1+**bx**+**dx**^2)	0.93	0.142282293	0.013776793	-0.002007015	-1.89805E-05	1.14818E-05	
		>2.0	y=**a**+**cx**+**ex**^2	0.978	0.159093324		-0.002460623		1.2138E-05	
	Euro II	<2.0	y=(**a**+**cx**+**ex**^2)/(1+**bx**+**dx**^2)	0.99	0.161234564	0.074607063	-0.001206231	-0.000335154	3.6292E-06	
		>2.0	y=(**a**+**cx**+**ex**^2)/(1+**bx**+**dx**^2)	0.98	50057.71156	38026.82833	8033.150994	1150.215685	-26.61240156	
	Euro III	<2.0	y=(**a**+**cx**+**ex**^2)/(1+**bx**+**dx**^2)	0.99	0.096521338	0.103000188	-0.000238314	-7.23554E-05	1.93331E-06	
		>2.0	y=**a**+**cx**+**ex**^2	0.54	0.09124181		-0.001682045		8.93739E-06	
NO_x	Euro I	All capacities	y=(**a**+**cx**+**ex**^2)/(1+**bx**+**dx**^2)	0.96	3.095607924	0.141192269	-0.006175676	-0.000503115	0.000421523	
	Euro II	All capacities	y=(**a**+**cx**+**ex**^2)/(1+**bx**+**dx**^2)	0.94	2.398097386	0.076699891	-0.011576236	-0.000499938	0.000119971	
	Euro III	All capacities	y=(**a**+**cx**+**ex**^2)/(1+**bx**+**dx**^2)	0.92	2.816405992	0.198187904	0.066873591	-0.001431755	-0.000463021	
PM	Euro I	All capacities	y=**a**+**cx**+**ex**^2	0.70	0.113797282		-0.00232673		2.2605E-05	
	Euro II	All capacities	y=**a**+**cx**+**ex**^2	0.71	0.086648957		-0.001421038		1.05592E-05	
	Euro III	All capacities	y=**a**+**cx**+**ex**^2	0.81	0.051499481		-0.000880012		8.11743E-06	
FC	Euro I	<2.0	y=(**a**+**cx**+**ex**^2)/(1+**bx**+**dx**^2)	0.98	144.6558266	0.067270936	-0.187518726	-0.000316808	0.009469874	
		>2.0	y=(**a**+**cx**+**ex**^2)/(1+**bx**+**dx**^2)	0.96	194.8899162	0.071928682	0.18722555	-0.000332188	0.009988524	
	Euro II	<2.0	y=(**a**+**cx**+**ex**^2)/(1+**bx**+**dx**^2)	0.97	142.2433943	0.049847679	-0.651010459	-0.000169078	0.013231348	
		>2.0	y=(**a**+**cx**+**ex**^2)/(1+**bx**+**dx**^2)	0.96	194.8899162	0.071928682	0.18722555	-0.000332188	0.009988524	
	Euro III	<2.0	y=(**a**+**cx**+**ex**^2)/(1+**bx**+**dx**^2)	0.95	161.9413328	0.122981533	2.183647639	-0.000775895	-0.012779891	
		>2.0	y=(**a**+**cx**+**ex**^2)/(1+**bx**+**dx**^2)	0.96	194.8899162	0.071928682	0.18722555	-0.000332188	0.009988524	

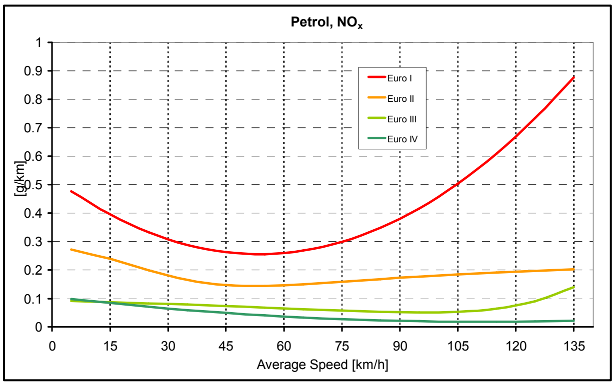

Figure B3-23: NO_x emission factors for petrol vehicles.

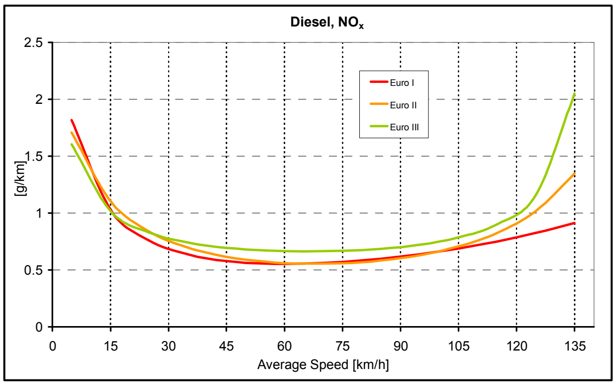

Figure B3-24: NO_x emission factors for diesel vehicles.

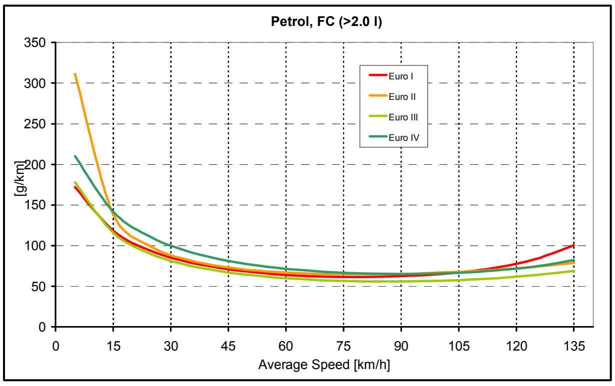

Figure B3-25: Fuel consumption, petrol vehicles (>2.0l).

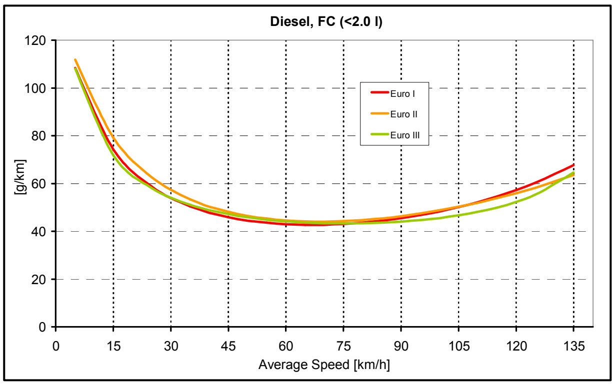

Figure B3-26: Fuel consumption, diesel vehicles (<2.0l).

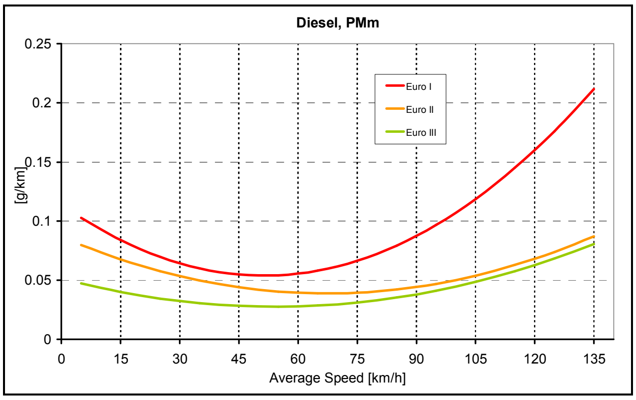

Figure B3-27: PM emission factors for diesel vehicles.

Design using Reference Test Patterns

An alternative approach was developed using the RTPs described in Section B3.2.3. Here, the emission data in the ARTEMIS LVEM database (see Section B3.5) were firstly averaged for each of the 15 RTPs. An emission function was then calculated using polynomial regression between the 15 RTP emission factors, expressed according to average speed. The emission factors covered CO, HC, NO_x, PM and CO_2 for pre-Euro I to Euro IV petrol and diesel vehicles, and according to engine size for CO_2. This approach has the advantage of being fully consistent with the traffic situation model, which is also based also on the RTP emission factors. The resulting emission functions are given in **Tables B3-50** and **B3-51**, and example functions are shown in **Figures B3-28** and **B3-29**. For these examples, the functions derived using speed ranges are also shown.

The choice of the regression model (power or 2nd to 5th order polynomial) was made for each data set with the following objectives: (i) to remain inside the envelope of the measured points as far as possible, in order to avoid systematic over- or underestimation of emission for some speed ranges, (ii) to correspond to the apparent shape of the points according to the average speed, (ii) to avoid large oscillations, (iv) to always give positive values, and (v) to be as simple as possible.

The shape of the curves at the highest speeds could nevertheless give unexpected values outside the speed range of the data. This was not the case for speeds lower than that of the slowest traffic situation (7 km/h), but it was sometimes the case for speeds higher than that of the traffic situation at 125 km/h. Therefore, in this case the model uses the values at 125 km/h.

Formulae of 2nd order polynomial function is: emission factor (g/km) = $a_0 + a_1V + a_2V^2$

Formulae of 3rd order polynomial function is: emission factor (g/km) = $a_0 + a_1V + a_2V^2 + a_3V^3$

Formulae of 4th order polynomial function is: emission factor (g/km) = $a_0 + a_1V + a_2V^2 + a_3V^3 + a_4V^4$

Formulae of 5th order polynomial function is: emission factor (g/km) = $a_0 + a_1V + a_2V^2 + a_3V^3 + a_4V^4 + a_5V^5$

Formulae of power function is: emission factor (g/km) = $a_0 . V^{a1}$

Where V is the average speed in km/h.

For V > 125 km/h, $EF(V) = EF(125)$

Table B3-50: Average-speed emission functions based on RTPs (CO, HC, NO_x and PM).

Pollutant	Fuel	Emission standard	Function shape	Function order	a_0	a_1 (x 100) but power: a_1	a_2 (x 10^4)	a_3 (x 10^6)	a_4 (x 10^8)	a_5 (x 10^{10})
CO	Petrol	Pre Euro I	Polyn.	2	42.711	-93.614	59.421			
		Euro I	Polyn.	2	6.385	-14.135	9.604			
		Euro II	Polyn.	4	2.416	-7.739	17.487	-21.637	10.490	
		Euro III	Polyn.	2	1.290	-4.327	4.914			
		Euro IV	Polyn.	2	0.635	-2.808	3.343			
	Diesel	Pre-Euro I	Polyn.	4	1.90201	-6.79900	12.19917	-9.6324	2.79	
		Euro I	Power		1.23173	-0.29353				
		Euro II	Polyn.	4	1.13262	-4.80989	9.23356	-8.05409	2.56591	
		Euro III	Polyn.	4	0.46897	-1.50224	2.43690	-2.11537	0.72139	
		Euro IV	Power		2.77591	-1.29524				
HC	Petrol	Pre-Euro I	Polyn.	2	4.79972	-9.24118	5.05465			
		Euro I	Polyn.	5	0.67736	-1.41946	-1.31149	6.50950	-6.27319	1.92706
		Euro II	Polyn.	3	0.27089	- 0.85798	1.02020	-0.38567		
		Euro III	Polyn.	2	0.03766	-0.07615	0.07248			
		Euro IV	Polyn.	2	0.00552	-0.00509	0.00768			
	Diesel	Pre-Euro I	Polyn.	2	0.24153	-0.32662	0.13967			
		Euro I	Power		0.23676	-0.47342				
		Euro II	Power		0.73731	-0,77230				
		Euro III	Power		0,49531	-0,84573				
		Euro IV	Power		0,07700	-0,46350				
NO_x	Petrol	Pre-Euro I	Polyn.	2	1.65743	-2.44728	2.74188			
		Euro I	Polyn.	2	0.50592	-0.72471	0.61938			
		Euro II	Polyn.	2	0.51310	-0.63039	0.36274			
		Euro III	Polyn.	2	0.12798	-0.16242	0.09518			
		Euro IV	Polyn.	2	0.07002	-0.11733	0.07567			
	Diesel	Pre-Euro I	Polyn.	2	2.43963	-4.73653	3.02793			
		Euro I	Polyn.	4	1.80731	-6.40833	10.68285	-6.93634	1.61796	
		Euro II	Polyn.	3	1.91079	-5.52505	6.68569	-2.26019		
		Euro III	Polyn.	4	2.25413	-9.34458	19.32741	-16.37522	5.03116	
		Euro IV	Polyn.	3	0.78737	-1.91047	2.56467	-0.70976		
PM	Petrol	Pre-Euro I	Polyn.	4	1.09796	-9.79572	32.34276	-42.09531	19.75152	
		Euro I	Polyn.	2	0.01217	-0.03603	0.03265			
		Euro II	Polyn.	3	0.00733	-0.02552	0.03021	-0.00589		
		Euro III	Power		0.00823	-0,22603				
		Euro IV	Power		0,00223	-0,04700				
	Diesel	Pre-Euro I	Polyn.	2	0.27111	-0.13179	0.03958			
		Euro I	Polyn.	2	0.11102	-0.26167	0.25323			
		Euro II	Polyn.	2	0.07856	-0.09372	0.08049			
		Euro III	Polyn.	2	0.05951	-0.12296	0.10223			
		Euro IV	Polyn.	2	0.07097	-0.26546	0.28696			

Table B3-51: Average-speed emission functions based on RTPs (CO_2).

Fuel	Engine size	Emission standard	Function shape	Function order	a_0	a_1 (x 100) but power: a_1	a_2 (x 10^4)	a_3 (x 10^6)	a_4 (x 10^8)	a_5 (x 10^{10})
Petrol	all	pre Euro	Polyn.	4	634.1	-2898.3	6108.3	-5414.6	1731.1	
		Euro I	Polyn.	4	587.7	- 2734.5	6031.3	-5488.3	1771.6	
		Euro II	Polyn.	4	644.5	- 3098.4	6903.2	-6416.4	2120.0	
		Euro III	Polyn.	4	521.9	- 1982.3	3928.5	-3390.2	1080.3	
		Euro IV	Polyn.	4	523.7	- 1654.4	2635.4	-1771.5	442.9	
Diesel	all	pre Euro	Polyn.	4	534.2	-2233.1	4484.8	-3645.4	1065.4	
		Euro I	Polyn.	4	380.3	-1179.0	1857.1	-1018.0	156.6	
		Euro II	Polyn.	4	457.9	-1733.6	3415.0	-2855.2	880.2	
		Euro III	Polyn.	4	429.7	-1516.1	2930.1	-2480.6	780.2	
		Euro IV	Polyn.	4	313.2	-959.4	1756.5	-1407.2	439.8	
Petrol	<1.4 l	pre Euro	Polyn.	5	514.0	-2958.6	8820.7	-12777.8	8889.9	-2356.8
		Euro I	Polyn.	4	476.9	-2085.1	4515.6	-4151.0	1377.7	
		Euro II	Polyn.	4	505.9	-2304.4	5188.9	-4898.6	1645.6	
		Euro III	Polyn.	4	434.0	-1508.0	2919.6	-2507.4	804.4	
		Euro IV	Polyn.	4	395.0	-1136.0	1731.8	-1086.0	248.5	
	1.4-2 l	pre Euro	Polyn.	5	650.5	-3836.2	11673.7	-17206.0	12087.9	-3223.5
		Euro I	Polyn.	4	648.7	-2988.0	6506.9	-5887.5	1895.6	
		Euro II	Polyn.	4	675.8	-3119.3	6698.3	-6064.5	1971.9	
		Euro III	Polyn.	4	561.3	-2131.9	4130.1	-3447.4	1060.1	
		Euro IV	Polyn.	4	505.3	-1839.2	3508.7	-2893.5	890.2	
	>2 l	pre Euro	Polyn.	5	941.7	-5290.0	14811.7	-20253.5	13426.0	-3421.8
		Euro I	Polyn.	5	1073.3	-7236.0	21825.1	-30712.8	20581.2	-5276.3
		Euro II	Polyn.	4	919.0	-4419.2	8918.2	-7235.0	2064.0	
		Euro III	Polyn.	4	649.8	-2267.5	4049.3	- 3182.1	935.8	
		Euro IV	Polyn.	3	672.0	-1723.5	2025.0	-755.0		
Diesel	<2 l	pre Euro	Polyn.	4	458.8	-1985.8	4266.0	-3888.8	1291.0	
		Euro I	Polyn.	4	390.3	-1350.1	2587.4	-2098.3	636.6	
		Euro II	Polyn.	4	437.1	-1673.7	3379.0	-2909.9	921.5	
		Euro III	Polyn.	4	412.0	-1449.1	2818.8	-2388.6	750.2	
		Euro IV	Polyn.	4	306.2	-856.8	1577.0	-1286.1	403.1	
	>2 l	pre Euro	Polyn.	4	570.8	-2269.5	4486.8	-3602.5	1036.6	
		Euro I	Polyn.	3	527.3	-1614.4	2327.3	-954.9		
		Euro II	Polyn.	4	561.8	-2176.3	4260.8	-3478.1	1037.9	
		Euro III	Polyn.	4	517.9	-2113.9	4475.9	-3938.1	1227.7	
		Euro IV								

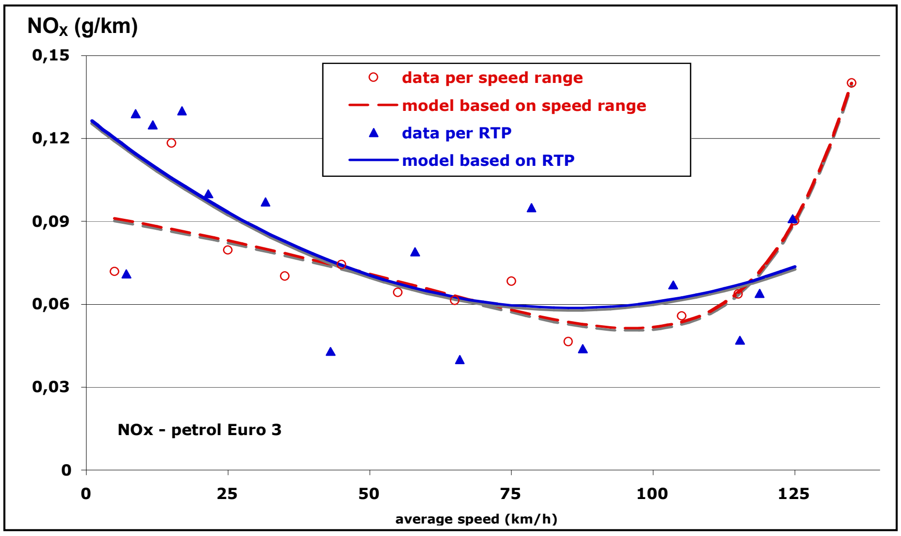

Figure B3-28: Petrol Euro III NO_x emission functions and data according to average speed, as designed through RTPs or through speed range averages.

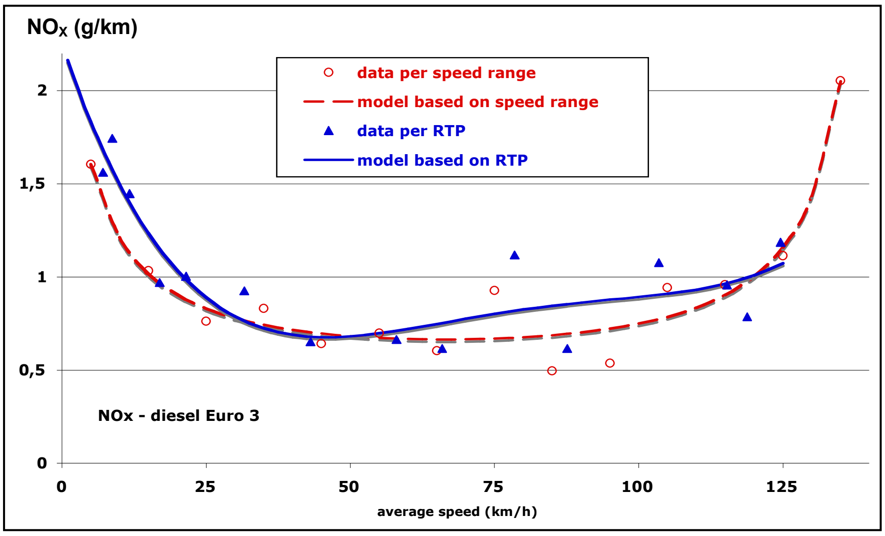

Figure B3-29: Diesel Euro III NO_x emission functions and data according to average speed, as designed through RTPs or through speed range averages.

Comparison of the two average speed models

The comparison of the second approach based on RTPs with the first one based on speed range averages showed some differences in terms of curve shape and emission level, sometimes up to a factor two. These differences may be due to the following:

- The homogenisation of the data with respect to the vehicle mileage, which was only conducted for the second method, thus giving fully standardised emission factors.
- The way in which the emission data are clustered - by 10 km/h speed ranges in the first method and by a statistical multi-dimensional clustering in the second method. The clustered emission factors can be very different between the two methods, as shown by **Figures B3-28** and **B3-29.**
- The choice of the equation type. In the first method the equation was selected for its adaptability to the high slope at low and high speeds, often making the extreme points (lowest and highest speeds) better adjusted than the other points. In the second method the equation is chosen mainly to remain within the envelope of the data points.

The differences between the two approaches show that such a model depends a great deal on the methodological assumptions. This is the reason why the second approach was developed - in order to be fully compatible with the main ARTEMIS traffic situation model. Indeed, in both approaches (traffic situations, average speed model based on RTP), the emission measurements are firstly aggregated into RTP emission factors, and then into traffic situations emission factor or into emission functions relating to average speed.

The range of vehicle categories and pollutants covered by each of the two methods differed slightly: The second method did not cover CO_2 for diesel Euro IV vehicles with an engine size > 2 l, and the first method did not cover pre-Euro I vehicles, diesel Euro IV vehicles and PM emissions from petrol cars. In addition, the first method considers fuel consumption and not CO_2, with the second method considering CO_2 only.

A speed-dependent emission model should nevertheless not be used to compare different driving patterns, as taking into account driving behaviour only through average speed is not accurate enough and too simplified: either the traffic situation model (Section B3.4.3), the kinematic regression model (Section B3.4.2) or an instantaneous model (Section B3.4.1) is necessary in such cases. A speed-dependent emission model could be used for a quick emission estimation, or if information on the driving patterns is especially poor, without allowing the use of another model: but even in this case it would be advisable to use the macro traffic situations defined in Section 3.4.2, and the corresponding emission factors defined in Section 3.4.6.

Reduction factors for future technologies

Due to the lack of both measurements and information in the literature, emission factors for future vehicle technologies were derived using assumed reduction factors.

Petrol vehicles

Considering the fact that Euro V emission standards will remain the same as those for Euro IV, the Euro IV equations can also be used for Euro V vehicles. As regards direct ignition petrol vehicles (DISI), both the literature and the limited available data suggest a reduction of around 10% in fuel consumption, and this can be used as a reduction factor against the respective technology emission factors. Pollutants emissions are assumed not to be altered by direct injection technology.

Diesel vehicles

Table B3-52 presents the reduction of emissions expected in Euro IV and V diesel vehicles based on the emissions of Euro III vehicles. These factors where derived from the ratios between the established Euro IV or expected Euro V emission standards and the emission standards of Euro III:

Table B3-52: Reduction factors for future diesel vehicle technologies.

	CO	HC	NO_x	PM mass	
Euro IV	0.781	0.833	0.5	0.5	x Euro III
Euro V	0.781	0.833	0.35	0.1	x Euro III

Table B3-53 presents the PM mass reduction potential of the installation of a diesel particulate filter (DPF) on a vehicle. The factors were derived under the assumption that the application of DPF leads to PM mass levels comparable to the expected Euro V limit

Table B3-53: Reduction of PMm emissions due to the addition of a diesel particulate filter

	PM	
Euro III + DPF	0.1	x Euro III
Euro IV + DPF	0.1	x Euro IV

B3.5 ARTEMIS light vehicle emission measurement database

Following on from the emission measurement campaign carried out within the project, a database was developed to combine the resulting data with those from other European studies (Joumard *et al.*, 2007).

B3.5.1 Objectives

One of the principal objectives of the ARTEMIS project was to improve the exhaust emission factors for passenger cars and light-duty vehicles by enlarging the emission factor database - especially for unregulated pollutants, recent technologies and light-duty vehicles.

The aim of the ARTEMIS database was to collect all emission measurements made in Europe for passenger cars and light-duty commercial vehicles. Such data can be obtained in the laboratory or on the road, but always over a driving cycle or sub-cycle. In order to be usable by the ARTEMIS partners, but also by any other research team in the field of the emissions from transport, the database contained not only the measured emissions but also all the explanatory parameters, where they were available. The database was also designed so that it could be easily updated in the future with new emission measurements.

B3.5.2 Database structure

The database was basically made up of three main tables and two secondary tables, as shown **Figure B3-30**. The three main tables were:

(i) A vehicle identification based on 103 parameters, providing information on the tested vehicles, such as testing laboratory, make, model, year of registration, size of engine, fuel type, *etc.*

(ii) A test identification, including the vehicle and driving cycle identification and 47 other test parameters, providing information on the measured tests, such as test date, technical details on the test procedure, dynamometer settings, *etc.*

(iii) An emission identification, including the test and pollutant identification, the emission factor itself and its units.

The tables *VEHICLES* and *TESTS* were connected on the basis of a 1:n relationship. This allowed one vehicle to be measured for several tests. A counter named *CHRONOLOGICAL_TEST-NB* allowed the data for one vehicle measured several times over the same driving cycle to be defined in terms of test order. The *EMISSION_DATA* were assigned to the corresponding vehicle and test conditions using the vehicle identifier, the test identifier and the *CHRONOLOGICAL_TEST-NB*. The ARTEMIS LVEM database is formatted as a MicroSoft Access database. It contains raw data (tables) plus a few queries giving an overview of the available data. There are no forms or macros included.

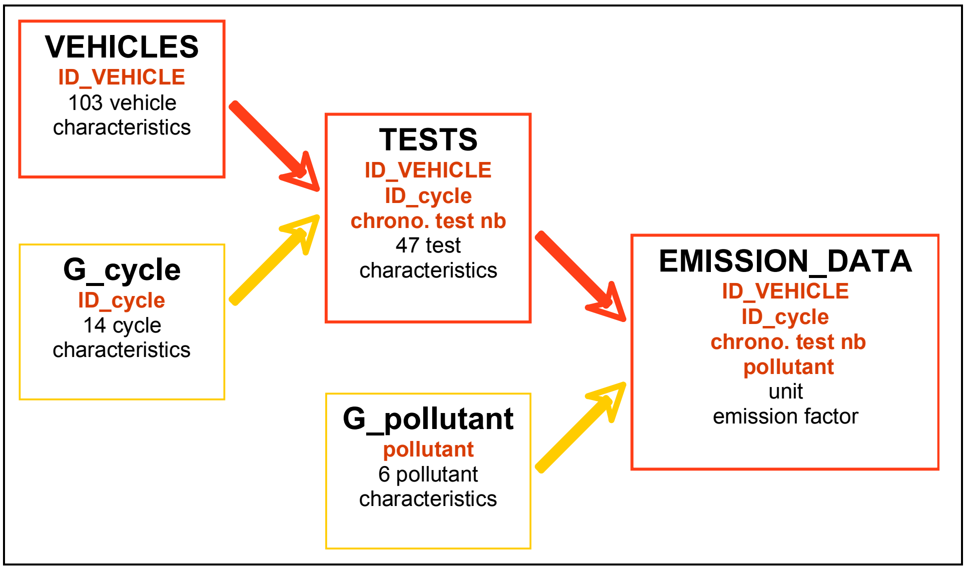

Figure B3-30: Simplified design of the database, including the three main tables and the two most important secondary tables.

B3.5.3 Data submission

A data sheet defines the format that should be used when submitting data for the ARTEMIS LVEM database. For every car involved, a separate copy of this Excel file should be used. This data sheet, detailed in (Joumard *et al.*, 2007), contains five sheets:

(i) *README* provides additional information and help on how to use the data sheet.

(ii) *car* summarises the characteristics of the tested vehicle.

(iii) *test xx* describes the test characteristics of the tested car - one copy of this sheet is needed for each cycle tested.

(iv) *instantaneous data test xx*: contains instantaneous data as a function of time. The use of this sheet for instantaneous data is recommended but not compulsory.

(v) *pollutant names*: lists the name convention for unregulated pollutants.

B3.5.4 Data harmonisation

The database includes functions allowing the harmonisation of the emission data. Four parameters are taken into account: the gearshift strategy, the vehicle mileage, the ambient air temperature, and the ambient air humidity. They are standardised at the following values, respectively: ARTEMIS strategy, 50 000 km, 23°C, 10.71 g H_2O/kg dry air. These four test parameters were found to have a quantifiable influence on the emission level (see Section B3.2.8). These corrections are quite important, and can be much higher for vehicle sub-classes or individual tests: between -17% and +30 % in average for a vehicle category and a pollutant. In addition, the total HC emission factor units can be harmonised in g eq. C_3H_8 or in g eq. CH_4 (see Section 3.1.2); the difference is about 9 %.

B3.5.5 Content

The ARTEMIS LVEM database merges emission data measured within the ARTEMIS project itself with data derived from other European measurement campaigns - such as PARTICULATES, MEET (data from INRETS, TNO, TRL, and LAT), HBEFA (mainly EMPA, TUEV), OSCAR (TRL, TNO) and additional INRETS and TNO data. The present version of the database contains data for 2,847 passenger cars and light commercial vehicles, measured between 1980 and 2004. For these vehicles, 12,685 tests were conducted when considering the sub-cycle level, and 18,824 tests when analysing at the cycle level. Regarding pollutants per vehicle and sub-cycle, 177,861 emission factors (g/km) are included for 404 pollutants. More than 25,000 of these emission factors are for unregulated pollutants.

B3.5.6 Public availability

In a first step, database was developed and used only by the ARTEMIS partners. After the completion of the project - and with the authorisation of all participating laboratories - the main part of the database is now available for anybody to use. It is managed by INRETS, but could be managed in the near future by another partner laboratory. The database is at the same time open for data submission, through the same laboratory.

B3.6 Summary and recommendations

B3.6.1 Accuracy of emission measurements

Eleven European laboratories worked together to study the influence of many parameters on the measurement of light vehicle emission factors. The overall aim was to improve the accuracy, reliability and representativeness of the emission factors. The parameters studies included driving patterns (driving cycles, gear choice behaviour, driver and cycle following), vehicle-related parameters (technical characteristics of the vehicle, emission stability, emission degradation, fuel properties, vehicle cooling and preconditioning), vehicle sampling (method, sample size), and laboratory-related parameters (ambient temperature and humidity, dynamometer setting, dilution ratio, heated line sampling temperature, PM filter preconditioning, response time, dilution air). The results were based upon a combination of literature reviews, around 2,700 specific tests on 183 vehicles, and on the reprocessing of data from more than 900 earlier tests. These tests concern the regulated atmospheric pollutants and pre-Euro I to Euro IV vehicles.

For seven parameters no systematic effect on emissions was observed, and only a qualitative effect could be stated for seven other parameters. However, six parameters had a clear and quantifiable effect on emissions and for five of these correction factors could be developed to normalise emission measurements: gearshift strategy, vehicle mileage, ambient temperature and humidity, dilution ratio. The sixth influencing parameter was the driving cycle, which was sometimes more significant than the fuel or the emission standard. The results led to a series of recommendations and guidelines for the determination of light-duty road vehicle emission factors in the future.

B3.6.2 Improvement of emission factor database

The emission models for light-duty road vehicles have been updated and greatly improved in ARTEMIS. This development was based on a targeted, in-depth measurement campaign, with more than 150 vehicles and about 3,500 tests for a large number of pollutants, both regulated and unregulated.

B3.6.3 Development of new models for hot exhaust emissions

ARTEMIS followed on from, and was designed to replace, the two main inventory models in use in Europe - MEET/COPERT III and the Handbook of Emission Factors (HBEFA), mainly used in Austria, Germany and Switzerland. In the ARTEMIS project, the most recent and comprehensive data on emissions were used to further develop a set of complementary sub-models. The base model calculates hot emissions for each vehicle category according to driving behaviour. It contains five alternative models:

- The main model considers traffic situations, with emission factors for each traffic situation.
- A simplified model, built on the same data, takes into account driving behaviour through average speed.
- A so-called kinematic model considers a limited number of aggregated kinematic parameters
- Two instantaneous models, which use a number of instantaneous vehicle operation parameters.

These models need input kinematic data of different complexity, and are therefore adapted to different uses. In the ARTEMIS road transport software (see PART I), they are linked to models which take into account the influence of several parameters, as cold start, the use of auxiliaries like air conditioning, vehicle mileage, ambient air temperature and humidity, road gradient and vehicle load, and evaporation.

B3.6.4 ARTEMIS light vehicle emission measurement database

The results of the measurements carried out by several European laboratories are included in a database specially designed for the project - the ARTEMIS LVEM database – to which can be added future European measurements.

B3.7 References

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B4 LIGHT COMMERCIAL VEHICLES

B4.1 Introduction

Emission factors for light commercial vehicles (LCVs)[14] were included in COPERT III (Ntziachristos and Samaras, 2000), but the method was based on data obtained from passenger cars. Furthermore, only pre-Euro I and Euro I vehicles were included in COPERT III, the emission factors only used average speed (via regression fits to the data) to define vehicle operation, and the values of the coefficients of determination for the regression functions were rather low. This Section of Part B describes how the data for LCVs were extracted for the ARTEMIS database, and subsequently used to develop new emission factors which took into account vehicle speed and load. The Section summarises the reports by Markewitz and Joumard (2005), and Joumard *et al.* (2007).

B4.2 Data extraction and vehicle classification

The first stage of the analysis involved extracting all LCVs ('light vans', 'vans' and 'mini-vans') from the ARTEMIS database (Kljun *et al*., 2005; Andre, 2005). Data were available from an ADEME programme carried out by INRETS (Joumard *et al*., 2001; Joumard *et al*., 2002; Joumard *et al*., 2003) and tests previously undertaken by TNO, EMPA and KTI. The database included 150 vehicles tested over 2,035 cycles. Specific driving cycles for LCVs were also developed for the programme. These cycles took into account not only vehicle usage but also load factors (André *et al*., 2000).

The vehicles were then grouped according to the classification recommended for use in ARTEMIS (Keller, 2005) which took into account the European categorisation based on vehicle tare weight:

- N1-I Vehicles used to transport goods, and whose tare weight is less than 1,305 kg,
- N1-II Vehicles used to transport goods, and whose tare weight ranges from 1,305 kg to 1,760 kg,
- N1-III Vehicles used to transport goods, and whose tare weight is greater than 1,760 kg and less than 3,859 kg.

Vehicles were also classified according to emission standard (pre-Euro I to Euro III), and the type of fuel used (diesel, petrol). Thus, 24 different vehicle classes were identified.

Table B4-1 summarises the distribution of vehicles in the database according to this classification. The size samples in the various classes were not equal. Of the 24 defined vehicle classes, 18 contained at least one vehicle, but some classes contained less than four vehicles and others contained more than ten. Furthermore, whereas six laboratories tested LCVs, no vehicle classes contained data from more than four laboratories. Only one Euro III vehicle was tested.

Table B4-1: Distribution of vehicles according to the size class, fuel and emission legislation

Size class	Fuel	Emission legislation			
		Pre-Euro I	Euro I	Euro II	Euro III
N1-I	Petrol	5	3		
	Diesel	2	4	11	
N1-II	Petrol	10	35	7	
	Diesel	15	9	4	1
N1-III	Petrol	1	4	2	
	Diesel	11	9	9	
Total		44	73	33	1

B4.3 Emission calculations

B4.3.1 Emissions as a function of average speed

For the individual test vehicles the emission data were examined as a function of the average speed of the corresponding driving cycle, with regression functions being fitted to the measurement points. The coefficients of determination were generally significant (greater than 0.7). However, for certain vehicles the values obtained were low (less than 0.3) due to the presence of tests carried out using cycles over which parameters other than average speed (*e.g.* acceleration) had a significant influence on emissions.

For each vehicle class described in **Table B4-1**, an average emission function was also calculated. It was assumed that each measurement within a vehicle class had the same weighting. The validity of using an average equation was tested

[14] Such vehicles are also often referred to as 'light-duty' vehicles (LDVs) or 'light goods' vehicles, although this can lead to confusion as passenger cars are also considered as LDVs by some authors, and such vehicles do not necessarily transport 'goods'. The term 'light commercial vehicles' is therefore used here.

statistically using Pearson's test. The aim of this test was to verify the hypothesis that the results calculated using the average equation were equivalent to either the raw data or the data obtained from the equation for each vehicle.

The results were then analysed in several steps. The first step involved separating the vehicles that satisfied Pearson's test from those which did not. Then, the vehicles that verified Pearson's test were separated into three groups as a function of the coefficient of determination obtained. Where the coefficient was higher than 0.7, the emission was considered to be dependent only on the average speed. If the coefficient of determination was between 0.5 and 0.7, the equation for the group of vehicles was considered to be satisfactory, but other parameters were sought to obtain a coefficient higher than 0.7. If the coefficient of determination was lower than 0.5 but the test was validated, the equation was only accepted if the addition of the parameter did not lead to any increase in the coefficient of determination. In this case, it was necessary to carry out additional work. For petrol vehicles, 18 validated emission factors were obtained (confirmation of Pearson's test and a coefficient of correlation higher than 0.7) – *i.e.* 34% of the equations – but for diesel vehicles there were only 12 – *i.e.* 12%. Eight diesel vehicle emission factors and six petrol vehicles emission factors were not validated by Pearson's test. It was therefore concluded that the emission factors were not only dependent on average speed.

B4.3.2 Correction for vehicle load factor

The load factor is a specific parameter relating to LCV use. Specific driving cycles have been created for LVCs to take into account the load factor. In ARTEMIS, the load factor was calculated for all vehicles and cycles using the following equation:

$$\tau = \frac{M_{test} - M_{empty}}{M_{empty}} \times 100$$

Where: τ = load factor

M_{test} = weight of the vehicle during the test
M_{empty} = vehicle tare weight

The load factor values obtained ranged from 0% to 91%. However, for around one in eight of the tests it was not possible to calculate the load factor due to the absence of data on the weight of the vehicle during the test. Furthermore, the load of a vehicle is not the only parameter influencing emissions, since the average-speed emission functions for groups with a low range of loads did not necessarily possess a high coefficient of determination, nor even validate Pearson's test.

The coefficients of the average-speed functions were found to be related to load. For example, where, for a given pollutant, the emission function is a second-order polynomial ($y = av^2 + bv + c$), the coefficients a, b and c are related to the load.

In order to define the links between the coefficients and the load factors, the following method was used. Speed ranges were defined in which the vehicle sample and load conditions were representative. The equation describing the pollutant emission as a function of load was formulated for these ranges (usually a second-order polynomial). The equation in each speed range was therefore $y = a'x^2 + b'x + c'$, with x being the load factor as a percentage of the tare weight. The coefficient of determination between this curve and the emission data was calculated. **Figure B4-1** shows an example of the variation in a coefficient with average speed. The results obtained for the coefficients of determination were 0.65 and 0.52 on average for diesel and petrol vehicles respectively. Equations for which the coefficient of determination was less than 0.2 were not used.

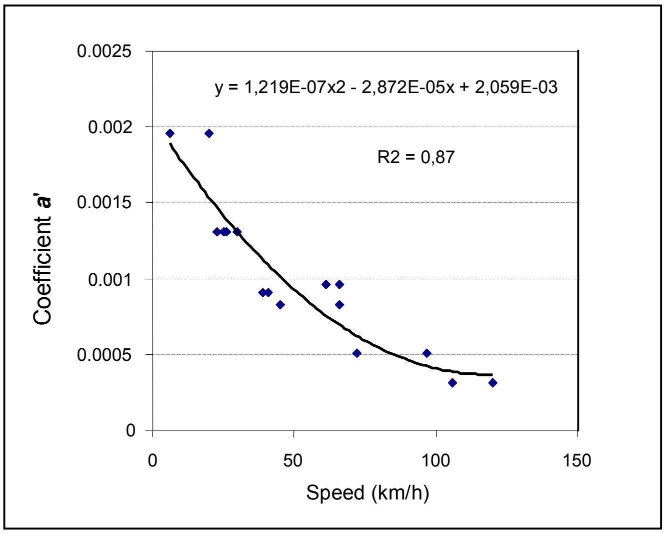


Figure B4-1: Coefficient ***a'*** of the HC emission function for the class N1-III Euro I diesel as a function of average speed.

For each speed range, the coefficients of the equation (***a'***, ***b'*** and ***c'*** of $y = a'x^2 + b'x + c'$) were linked with the average speed. An equation linking each coefficient to the speed was then calculated. If the coefficient of determination was unsatisfactory (less than 0.5), the speed ranges were revised until a better coefficient was obtained, otherwise the group of vehicles was withdrawn from the load study. The coefficients obtained were 0.75 and 0.76 on average for diesel and petrol vehicles respectively. The equation of each coefficient was then incorporated in the pollutant emission equation. The combined equations for each vehicle class are given in **Tables B4-2** to **B4-7.**

Table B4-2: Emissions as a function of average speed and load – diesel vehicles, N1-I.

Emission legislation	Pollutant	Load range (%)	Equation Factor; E (g/km): emission (g/km); v: average speed (km/h), p: load (%)
Pre-Euro I	CO		$E= 5,83x10^{-4}v^2 - 6,99x10^{-2}v + 2,53$
	CO_2		$E= 0,146v^2 - 15,6v + 590$
	FC		$E= 4,75x10^{-2}v^2 - 5,05v + 191$
	HC		$E= 9,92x10^{-5}v^2 - 1,15x10^{-2}v + 0,485$
	NO_x		$E= 4,41x10^{-4}v^2 - 4,46x10^{-2}v + 1,69$
	PM[15]		$E= 5.8x10^{-5}v^2-0.0086v+0.45$
Euro I	CO	0-25	$E= (-3,83x10^{-6}v^2 + 3,30x10^{-4}v + 1,28x10^{-2})p+1,84x10^{-4}v^2 - 2,50x10^{-2}v + 1,26$
	CO_2	0-25	$E= (-0,0012v^2 + 0,0654v + 6,0995)p+(0,0249v^2 - 2,3223v + 176,92)$
	FC	7-25	$E= (-5,86x10^{-5}v^2 + 8,84x10^{-3}v - 4,91x10^{-1})p^2+(0,0019v^2 - 0,2989v + 18,565)p+ 0,4963v - 32,605$
	HC	7-25	$E= (2,42x10^{-5}v - 2,43x10^{-3})p^2+(-8,44x10^{-4}v + 8,41x10^{-2})p+ 0,0041v - 0,3375;\ E \geq 0,04$
	NO_x	7-25	$E= (4,80x10^{-5}v - 6,80x10^{-3})p^2+(-1,73x10^{-3}v + 0,246)p+1,02x10^{-2}v - 0,955$
	PM		$E= -1,71x10^{-5}v^2 + 2,419x10^{-3}v + 2,31x10^{-2}$
Euro II	CO		$E= 8,66x10^{-5}v^2 - 1,56x10^{-2}v + 0,912$
	CO_2		$E= 0,0245v^2 - 3,4055v + 273,56$
	FC		$E= 8,35x10^{-3}v^2 - 1,20v + 84,3$
	HC		$E= 3,47x10^{-5}v^2 - 6,17x10^{-3}v + 0,293$
	NO_x		$E= 2,23x10^{-4}v^2 - 2,89x10^{-2}v + 1,47$
	PM		$E= 1,50x10^{-5}v^2 - 2,19x10^{-3}v + 0,113$

Table B4-3: Emissions as a function of average speed and load – diesel vehicles, N1-II.

Emission legislation	Pollutant	Load range (%)	Equation Factor; E (g/km): emission (g/km); v: average speed (km/h), p: load (%)
Pre-Euro I	CO	0-62	$E= (-2,11x10^{-7}v^2 + 3,76x10^{-5}v - 2,03x10^{-3})p^2+(1,33x10^{-5}v^2 - 2,70x10^{-3}v + 0,161)p+(1,46x10^{-4}v^2 - 1,14x10^{-2}v + 0,398)$
	CO_2	0-62	$E= (6,21x10^{-6}v^2 - 2,35x10^{-3}v + 7,58x10^{-2})p^2+(2,49x10^{-4}v^2 + 7,25x10^{-2}v - 4,04)p+0,0211v^2 - 3,7377v + 357,35$
	FC	0-62	$E= (2,45x10^{-6}v^2 - 6,32x10^{-4}v + 2,72x10^{-2})p^2+(2,25x10^{-2}v - 1,77)p+(7,98x10^{-3}v^2 - 1,31 v + 125)$
	HC	6-62	$E= (-5,29x10^{-8}v^2 + 1,09x10^{-5}v - 8,56x10^{-4})p^2+(3,48x10^{-6}v^2 - 7,24x10^{-4}v + 5,76x10^{-2})p -4,39x10^{-5}*v^2 + 5,54x10^{-3}v – 0,138;\ E \geq 0,05$
	NO_x	0-62	$E= (-3,23x10^{-5}v + 2,42x10^{-3})p^2+(1,41x10^{-3}v - 6,83x10^{-2})p-1,17x10^{-2}v + 1,61;\ E \geq 0,5$
	PM	6-50	$E= (-1,33x10^{-8}v^2 + 9,48x10^{-6}v - 1,02x10^{-3})p^2+(4,72x10^{-6}v^2 - 1,19x10^{-3}v + 8,35x10^{-2})p+2,82x10^{-6}v^2 + 5,36x10^{-3}v – 0,341$
Euro I	CO	5-32	$E=(4,998x10^{-8}v^2 + 1,830x10^{-5}v - 2,301x10^{-3})p^2+(5,086x10^{-6}v^2 - 1,822x10^{-3}v + 0,1435)p+9,10x10^{-5}v^2 - 1,48x10^{-2}v + 0,499$
	CO_2	0-32	$E=(1,70x10^{-4}v^2 - 1,37x10^{-2}v + 1,38)p+2,81x10^{-2}v^2 - 4,13v + 306$
	FC	0-32	$E=(-2,99x10^{-6}v^2 + 7,84x10^{-4}v - 8,45x10^{-3})p^2+(8,33x10^{-5}v^2 - 2,16x10^{-2}v + 0,359)p+1,17x10^{-2}v^2 - 1,60v + 108$
	HC		$E= 2,51x10^{-5} v^2 - 5,56x10^{-3}v + 0,342$
	NO_x	0-32	$E=(-6,47x10^{-7}v^2 + 1,01x10^{-4}v - 2,49x10^{-3})p^2+(2,85x10^{-5}v^2 - 4,14x10^{-3}v + 0,106)p+1,83x10^{-5}v^2 + 2,66x10^{-3}v + 0,640$
	PM	0-32	$E=(4,85x10^{-6}v - 1,03x10^{-4})p^2+(-1,85x10^{-4}v + 6,48x10^{-3})p+1,17x10^{-3}v + 2,88x10^{-2}$
Euro II	CO		$E= 1,65x10^{-5}v^2 - 5,19x10^{-3}v + 0,412$
	CO_2		$E= 0,0343v^2 - 5,1159v + 367,86$
	FC		$E= 0,0105v^2 - 1,513v + 107,74$
	HC		$E= -5,49x10^{-7}v^2 - 4,38x10^{-4}v + 7,29x10^{-2}$
	NO_x		$E= 1,85x10^{-4}v^2 - 2,16x10^{-2}v + 1,42$
	PM		$E=5,03x10^{-6}v^2-7x10^{-4}v+0,049$

[15] MEET equation was used because of the lack of data for ARTEMIS project.

Table B4-4: Emissions as a function of average speed and load – diesel vehicles, N1-III.

Emission legislation	Pollutant	Load range (%)	Equation Factor; E (g/km): emission (g/km); v: average speed (km/h), p: load (%)
Pre-Euro I	CO	0-100	$E=(1,37x10^{-7}v^2 - 1,27x10^{-5}v + 3,98x10^{-4})p^2+(-1,22x10^{-5}v^2 + 1,12x10^{-3}v - 3,73x10^{-2})p+ 4,12x10^{-4}v^2 - 4,86x10^{-2}v + 2,25$
	CO_2	0-100	$E=(-4,06x10^{-6}v^2 + 7,71x10^{-4}v + 2,86x10^{-2})p^2+(3,84x10^{-4}v^2 - 6,11x10^{-2}v - 4,07)p+ 0,0444v^2 - 6,1129v + 509,84$
	FC	0-100	$E=(-2,74x10^{-6}v^2 + 3,79x10^{-4}v + 7,49x10^{-3})p^2+(2,52x10^{-4}v^2 - 3,25x10^{-2}v - 1,11)p+ 0,0115v^2 - 1,6528v + 161,8$
	HC	0-100	$E=(6,67x10^{-9}v^2 - 6,78x10^{-7}v + 5,95x10^{-5})p^2+(-6,16x10^{-7}v^2 + 9,76x10^{-5}v - 8,61x10^{-3})p+3,77x10^{-5}v^2 - 6,82x10^{-3}v + 0,436$
	NO_x	0-100	$E=(2,66x10^{-7}v^2 - 4,83x10^{-5}v + 2,66x10^{-3})p^2+(-2,62x10^{-5}v^2 + 4,79x10^{-3}v - 0,262)p+(0,0009v^2 - 0,1511v + 8,3427)$
	PM	0-100	$E=(1,34x10^{-6}v + 2,89x10^{-5})p^2+(-1,36x10^{-4}v - 3,88x10^{-3})p+1,49x10^{-5}v^2 + 6,51x10^{-4}v + 0,352$
Euro I	CO	7-50	$E=(1,79x10^{-7}p^2-1,87x10^{-5}p+4,3x10^{-4})v^2+(-2,1x10^{-5}p^2+2,66x10^{-3}p-6,94x10^{-2})v+(2,88x10^{-3}p^2-0,195p+4,05)$
	CO_2	7-50	$E=(2,56x10^{-5}p^2-1,89x10^{-3}p+0,0654)v^2+(7,4x10^{-4}p^2+0,108p-7,2126)v+(0,304p^2-19,8p+662,1)$
	FC	7-50	$E=(2,37x10^{-5}p^2-1,3x10^{-3}p+0,0279)v^2+(-2,73x10^{-3}p^2+0,176p-3,8935)v+(0,193p^2-11,1p+262,46)$
	HC	7-50	$E=(1,219x10^{-7}v^2 - 2,872x10^{-5}v + 2,059x10^{-3})p^2+(-7,883x10^{-6}v^2 + 1,743x10^{-3}v - 1,157x10^{-1})p+ 1,357x10^{-4}v^2 - 2,788x10^{-2}v + 1,679; E\geq0$
	NO_x		$E= 3,75x10^{-4}v^2 - 4,51x10^{-2}v + 2,24$
	PM	0-50	$E=(-2,176x10^{-6}v^2 + 3,695x10^{-4}v - 1,760x10^{-2})p+(8,98x10^{-5}v^2 - 1,33x10^{-2}v + 0,642); E\geq0,03$
Euro II	CO	0-30	$E=(9,25x10^{-7}v^2 - 1,40x10^{-4}v + 4,75x10^{-3})p^2+(-3,36x10^{-5}v^2 + 5,14x10^{-3}v - 1,90x10^{-1})p+2,49x10^{-4}v^2 - 4,00x10^{-2}v + 1,88; E\geq0,01$
	CO_2	0-30	$E=(2,08x10^{-4}v^2 - 2,51x10^{-2}v + 0,331)p^2+(-4,08x10^{-3}v^2 + 5,83x10^{-1}v - 9,10)p+5,49x10^{-2}v^2 - 7,89v + 436$
	FC	0-30	$E=(-1,74x10^{-5}v^2 + 2,24x10^{-3}v - 0,111)p^2+(6,85x10^{-4}v^2 - 8,21x10^{-2}v + 4,54)p+8,66x10^{-3}v^2 - 1,19v + 87,6$
	HC	0-30	$E=(1,85x10^{-7}v^2 - 2,67x10^{-5}v + 1,08x10^{-3})p^2+(-6,87x10^{-6}v^2 + 1,02x10^{-3}v - 4,35x10^{-2})p+ 5,81x10^{-5}v^2 - 8,99x10^{-3}v + 0,427; E\geq0,01$
	NO_x		$E= 4,03x10^{-4}v^2 - 4,82x10^{-2}v + 2,25$
	PM	0-30	$E=(-8,52x10^{-8}v^2 + 1,26x10^{-5}v - 3,42x10^{-4})p^2+(2,49x10^{-6}v^2 - 3,36x10^{-4}v + 8,83x10^{-3})p+8,98x10^{-6}v^2 - 1,25x10^{-3}v + 0,114$

Table B4-5: Emissions as a function of average speed and load – petrol vehicles, N1-I.

Emission legislation	Pollutant	Load range (%)	Equation Factor; E (g/km): emission (g/km); v: average speed (km/h), p: load (%)
Pre-Euro I	CO		$E= 7,75x10^{-3}v^2 -0,889v + 32,4$ (Only hot cycles)
	CO_2		$E= 0,0219v^2 - 3,388v + 307,69$
	FC		$E= 0,0092v^2 - 1,233v + 103,07$
	HC		$E= 1,95x10^{-4}v^2 - 4,51x10^{-2}v + 3,22$
	NO_x		$E= -2,24x10^{-5}v^2 + 2,71x10^{-2}v + 1,04$
Euro I	CO		$E= 3,09x10^{-3}v^2 - 0,273v + 8,07$
	CO_2		$E= 0,0372v^2 - 5,3731v + 398,66$
	FC		$E= 0,0092v^2 - 1,233v + 103,07$
	HC		$E= 5,13x10^{-5}v^2 - 7,93x10^{-3}v + 0,422$
	NO_x		$E= -8,15x10^{-6}v^2 - 1,03x10^{-3}v +0, 729$

Table B4-6: Emissions as a function of average speed and load – petrol vehicles, N1-II.

Emission legislation	Pollutant	Load range (%)	Equation Factor; E (g/km): emission (g/km); v: average speed (km/h), p: load (%)
Pre-Euro I	CO	0-100	$E=(1{,}97x10^{-5}v^2 - 4{,}42x10^{-3}v + 0{,}35)p+0{,}0087v^2 - 1{,}2106v + 42{,}747$
	CO_2		$E= 0{,}055v^2 - 8{,}0246v + 486{,}46$
	FC		$E= 0{,}023v^2 - 3{,}3138v + 182{,}39$
	HC		$E= 8{,}91x10^{-4}v^2 - 0{,}142v + 5{,}80$
	NO_x	0-100	$E=(-8{,}80x10^{-6}v^2 + 1{,}43x10^{-3}v + 4{,}47x10^{-3})p+3{,}38x10^{-4}v^2 - 3{,}94x10^{-2}v + 1{,}83$
Euro I	CO	12-43	$E=(-7{,}56x10^{-6}*v^2 + 6{,}92x10^{-4}v - 1{,}29x10^{-2})p^2+(4{,}86x10^{-4}*v^2 - 4{,}64x10^{-2}v + 0{,}974)p+(-5{,}08x10^{-3}v^2 + 0{,}497v - 9{,}28)$; $E\geq0{,}01$
	CO_2	0-100	$E=(-1{,}96x10^{-5}v^2 + 3{,}18x10^{-3}v - 0{,}111)p^2+(1{,}57x10^{-3}v^2 - 0{,}244v + 8{,}82)p+4{,}21x10^{-2}v^2 - 5{,}70v + 371$
	FC		$E= 0{,}0587v^2 - 8{,}578v + 501{,}9$
	HC		$E= 5{,}81x10^{-5}v^2 - 8{,}35x10^{-3}v + 0{,}396$
	NO_x		$E= 9{,}43x10^{-5}v^2 – 6{,}58x10^{-3}v + 0{,}484$
Euro II	CO	4-56	$E=(8{,}37x10^{-7}v^2 - 1{,}43x10^{-4}v + 6{,}56x10^{-3})p^2+(-1{,}19x10^{-5}v^2 + 5{,}52x10^{-3}v - 0{,}255)p+6{,}86x10^{-4}v^2 – 0{,}112v + 4{,}63$
	CO_2		$E= 8{,}48x10^{-2}v^2 - 12{,}8v + 635$
	FC		$E= 0{,}0248v^2 - 3{,}719v + 191{,}22$
	HC	4-56	$E=(1{,}69x10^{-7}v^2 - 3{,}32x10^{-5}v + 1{,}83x10^{-3})p^2+(-5{,}85x10^{-6}v^2 + 1{,}24x10^{-3}v - 6{,}60x10^{-2})p+7{,}10x10^{-5}v^2 - 1{,}33x10^{-2}v +0{,}641$
	NO_x	0-56	$E=(4{,}29x10^{-7}v^2 - 3{,}58x10^{-5}v + 1{,}45x10^{-3})p^2+(-1{,}56x10^{-5}v^2 + 1{,}46x10^{-3}v - 5{,}16x10^{-2})p+1{,}52x10^{-4}v^2 - 1{,}61x10^{-2}v + 0{,}684$

Table B4-7: Emissions as a function of average speed and load – petrol vehicles, N1-III.

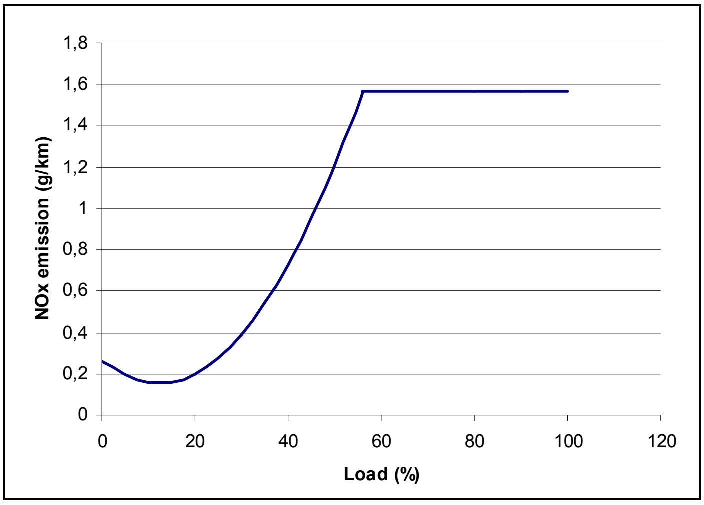
Emission legislation	Pollutant	Load range (%)	Equation Factor; E (g/km): emission (g/km); v: average speed (km/h), p: load (%)
Euro I	CO	7-87	$E=(-1{,}41x10^{-4}v^2 + 1{,}27x10^{-2}v + 5{,}24x10^{-2})p+(6{,}31x10^{-3}v^2 - 0{,}642v + 15{,}3)$; $E\geq1$
	CO_2		$E= 0{,}0803v^2 - 11{,}572v + 632{,}69$
	FC		$E= 0{,}0272v^2 - 3{,}8434v + 208{,}16$
	HC		$E= 1{,}14x10^{-4}v^2 - 1{,}41x10^{-2}v + 0{,}692$
	NO_x		$E= 9{,}52x10^{-5}v^2 - 8{,}96x10^{-3}v + 0{,}565$
Euro II	CO		$E= 7{,}40x10^{-4}v^2 – 0{,}122v + 6{,}16$
	CO_2		$E= 0{,}0876v^2 - 13{,}253v + 644{,}56$
	FC		$E= 0{,}0275v^2 - 4{,}1999v + 207{,}56$
	HC		$E= 1{,}01x10^{-5}v^2 - 5{,}56x10^{-3}v + 0{,}484$; $E\geq0{,}01$
	NO_x		$E= 1{,}20x10^{-5}v^2 - 5{,}43x10^{-3}v + 0{,}535$

For the vehicle classes and pollutants where no load range is given in **Tables B4-2** to **B4-7**, none of the emission factors were found to be linked to the vehicle load factor.

For the other groups, equations defining the emission as a function of average speed and load were established. **Figure B4-2** shows an example of a NO_x emission curve as a function of the load factor at 50 km/h. The equations had average coefficients of determination of 0.56 for diesel vehicles and 0.61 for petrol vehicles. This shows that the load parameter had a significant impact on the precision of the emission factor equation. An emission factor equation was considered as satisfactory when the Pearson test was validated and the coefficient of determinations was higher than 0.7. An equation was considered as valid but in need of further analysis when it was validated by Pearson's test and the two coefficients of determination were higher than 0.5 (and did not belong to the previous case). For 66% of groups containing diesel vehicles and 64% of the groups containing petrol vehicles, the equation representing the group had a coefficient of determination higher than 0.5, and could therefore be considered to be more robust than the equations used in COPERT.

For each of the equations obtained, and in particular for those including the load factor, it was necessary to model the emission behaviour outside the load conditions studied. The lower and higher values of the emission at the limit test load were compared with the values calculated at 0% and 100% respectively. When the difference was greater than 30 %, the equation was not used outside the study limits and the value outside the limits was assumed to be equal to that at the nearest boundary. In other cases, the calculation was carried out on the basis of the equation for any load or speed. The load ranges are indicated in **Tables B4-2** to **B4-7**, as applicable.

Figure B4-2: NO_x emission factor for N1-II Euro II petrol vehicles at 50 km/h as a function of load factor.



B4.4 Summary and conclusions

After extracting the emission data for LCVs from the ARTEMIS database, it was possible to formulate equations describing emission factors for these vehicles as a function of average speed and load factor. This method was used to statistically validate 97% and 96% of the emission factors for diesel and petrol LCVs respectively. Furthermore, a considerable improvement in the precision of the equations was observed. In COPERT, the average coefficient of determination was 0.39 for diesel LCVs and 0.49 for petrol LCVs. By updating the data in ARTEMIS and calculating the emission factors by using only the average speed as parameter, slight improvements in the coefficient of determination could be observed (0.41 for diesel vehicles and 0.5 for petrol vehicles). However, by adding load as a parameter, the average coefficient of determination changed to 0.59 for diesel vehicles and to 0.56 for petrol vehicles. In addition, whereas COPERT only deals with pre-Euro I and Euro I vehicles, this study was able to define emission factors for Euro II vehicles. However, further development of the emission factors is required, especially for post-Euro II vehicles.

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B5 HEAVY-DUTY VEHICLES

B5.1 Background

This Section of Part B summarises the ARTEMIS investigations into emissions from heavy-duty vehicles (HDVs). The HDV work featured close co-operation with the COST Action 346[16] and the Handbook of Emission Factors (HBEFA) project, and provided a great deal of insight into the emission behaviour of modern vehicles. The Section is based primarily upon the report by Rexeis *et al*. (2005), which should be consulted where more detailed information is required.

The main aims of the HDV work were:

(i) *To collect a large amount of HDV emission data from a range of European sources.* During the data collection exercise, emission measurements for 102 heavy-duty engines and eight vehicles were obtained from ARTEMIS and other national and international programmes, culminating in the most extensive database for HDV emissions in Europe. Data from dynamometer tests and on-board measurements on 50 vehicles were used for model validation purposes (Rexeis *et al*., 2005).

(ii) *To develop a model capable of accurately simulating emission factors for all types of HDV over any driving cycle and for various vehicle loads and gradients.* The resulting tool – PHEM (Passenger car and Heavy-duty Emission Model) - estimates fuel consumption and emissions (CO, THC, NO_x and PM) based on the instantaneous engine power demand and engine speed during a driving cycle specified by the user. The model combines steady-state engine maps with correction functions for transient operation.

(iii) *To acquire the necessary model input data*. In addition to the collection and analysis of vehicle and engine data, representative driving cycles were developed as model inputs. These were obtained through a review of the literature, an extensive analysis of all available on-board measurement data from driving behaviour studies, and a tailored measurement programme. To obtain more accurate emission factors, the effects of fuel quality, level of vehicle maintenance and various other factors were also investigated in detail.

(iv) *To generate a database of emission factors for the ARTEMIS inventory model.* An emission factor and fuel consumption database for conventional HDVs was compiled using PHEM, based upon typical vehicle data, engine data and representative driving cycles. Emission factors were produced for almost 170,000 combinations of pollutant, vehicle category, Euro class, driving cycle, vehicle load and road gradient.

B5.2 Model development

B5.2.1 Overview

Different HDV configurations often use the same engine. Measurements on a single engine can therefore potentially be used to estimate emissions from several different types of in-service vehicle. However, it is also essential to take into account the combined effects of road gradient and vehicle load, which greatly influence driving behaviour and therefore emission levels. To measure these effects in the laboratory an extensive and very expensive programme would be needed, whereas these effects can be simulated accurately using a model. Overall, the PHEM modelling method covers a much broader range of vehicles and driving conditions than a chassis dynamometer-based programme could ever produce within an acceptable budget. This clearly improves the reliability of the resulting fleet emission factors. The model is also capable of providing emission factors for an unlimited number of traffic situations, and its development has led to a much better understanding of the emission behaviour of modern HDVs.

Extensive use has been made of existing measurements via a co-ordinated data collection exercise involving all partners from DACH-NL[17] and COST 346. The ARTEMIS measurement programme was then designed to fill any gaps in the understanding, and to develop a method capable of incorporating the available data in a consistent way. The data obtained during the new measurement programme were added to the existing database.

A modelling methodology based upon interpolation from steady-state emission maps was chosen for PHEM, since a large number of such maps were already available. For a given driving cycle and road gradient, the required engine power is calculated each second, based on the driving resistance and losses in the transmission system. Engine speed is calculated from the transmission ratios and a gear-shift model. To allow for the effects of transient vehicle operation on emissions, the results from the steady-state maps are altered using transient correction functions. The ARTEMIS measurement programme and the development of the modelling approach are described in more detail later in this Section.

[16] http://www.cordis.lu/cost-transport/src/cost-346.htm
[17] DACH-NL relates to the group of countries involved in the development of HBEFA (D = Germany, A = Austria, CH = Switzerland, NL = Netherlands).

B5.2.2 Engine test bed measurements

The engine test bed measurements provided both the steady-state engine emission maps (emissions as a function of engine speed and engine torque), and data for the development of correction functions to account for the difference between the emission behaviour over steady-state and transient cycles. For the former, the main task was to develop a methodology which was able to make the best use of all the emission map formats in the database - different maps had been measured in such a way that real-world engine loads could be interpolated accurately from one overall engine map. From the whole data collection campaign, measurements on 102 engines were available. For 12 of the engines the only available emission maps were those based on the ECE-R49 and the ESC. For the other engines, additional off-cycle points had been measured during the steady-state tests. For 27 engines, transient tests and complete steady-state emission maps were available. Most of these engines had already been measured according to the complete ARTEMIS protocol, which is described below. Most of the engines were taken from HDVs which had been in use for between two months and two years, with regular service intervals.

Steady-state measurements

The steady-state tests included in the ARTEMIS programme were the ECE-R49 test, the ESC test, and the ARTEMIS test. The ECE-R49 and the ESC were performed as described in the corresponding EC documents. This also included the recording of the full-load curve. For the development of real-world emission factors for modern engines, the assessment of steady-state engine maps has shown that it is essential to incorporate off-cycle measurements. Since electronic engine control systems - used from Euro II onwards - allow different injection timing within the engine map, optimisation in the specific fuel consumption can result in increased NO_x emissions outside of the homologation test points. The common-rail injection systems used in Euro III engines give additional degrees of freedom, such as the possibility for pre- and post-injection, and offer the possibility of altering PM emissions within the engine map. For the ARTEMIS steady-state test, 29 points were added to the ECE-R49 and ESC in order to assess off-cycle emissions. **Figure B5-1** shows the measurement points for the ARTEMIS programme. Wherever possible, a PM emission map was measured. Since each point had to be run for a rather long time to collect enough PM mass on the filter, this was not possible for every engine. Where the time schedule did not allow the measurement of PM mass for each point, measurements were made at a reduced number of points (Rexeis *et al*., 2005).

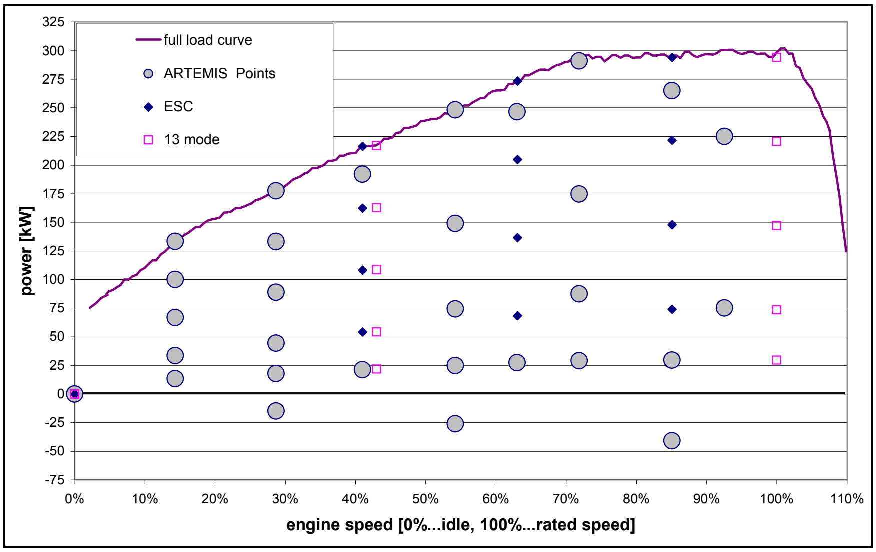


Figure B5-1: Steady-state points measured in the ARTEMIS programme (example full-load curve).

Figure B5-2 shows NO_x emission maps for typical Euro I, Euro II and Euro III engines. The emission maps are normalised for engine speed and engine power, and the emission values are given in g/kWh rated power. This unit is used in the vehicle emission model, and allows engines with different rated power to be compared directly. The typical NO_x emission maps for Euro I (and pre-Euro I - not shown) engines were very smooth. The NO_x levels from Euro II engines were lower at the ECE-R49 test points, but off-cycle levels were higher than for Euro I engines. The injection timing in the Euro II engines is retarded at the official test points, resulting in lower NO_x but higher fuel consumption and PM emissions. Given the demands for low specific fuel consumption, for many engine models an earlier injection time is programmed for off-cycle points. The Euro III legislation limits NO_x emissions between the three engine speeds of the homologation test (ESC). As a result, the Euro III NO_x emission maps exhibited a 'trough' between the highest and lowest engine speeds of the ESC. Outside this range, Euro III engines are also optimised for specific fuel consumption, resulting in increased NO_x emissions. As real-world driving conditions are likely to cover all areas of the engine map, and not just the legislative test points, real-world NO_x emissions can differ significantly from those during type approval.

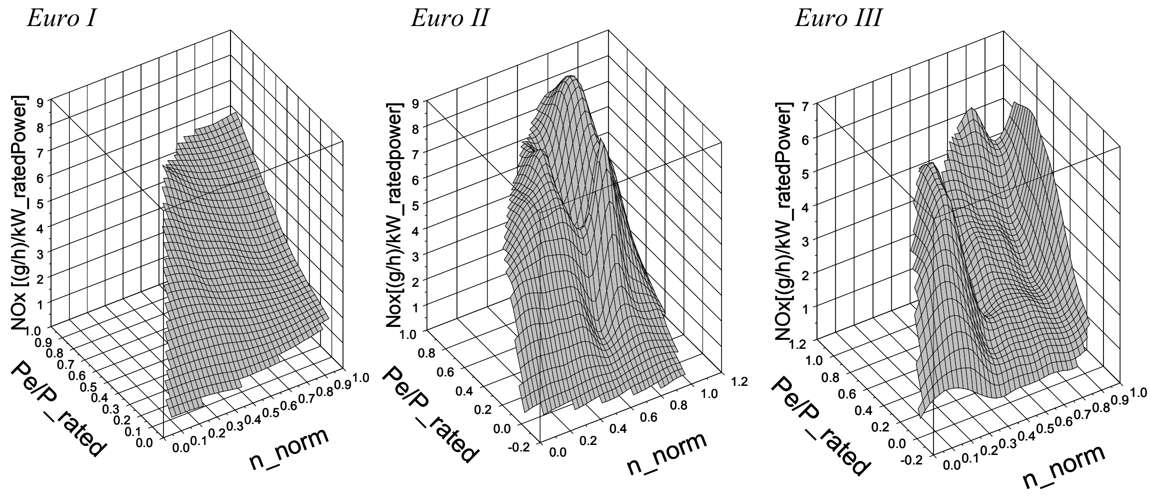


Figure B5-2: Typical steady-state NO_x emission maps for Euro I, Euro II and Euro III engines.

Measurements over the ECE-R49 test showed that only small reductions in NO_x emission levels had been achieved between Euro I and Euro II. However, NO_x values over the total engine map were, on average, at the same level for Euro I and Euro II. This indicated that the Euro II engines had higher emissions over the points not covered by the ECE-R49 test. The Euro III engines exhibited lower NO_x emissions than the Euro II engines over both the type approval test and the total engine map. This resulted from the broader range covered by the ESC test. The differences between the engine control strategy at the type approval points and the strategy at the other points of the engine map resulted in emission levels from Euro II and Euro III engines in real-world driving which exceeded the corresponding emission limits. CO and HC emissions decreased from pre-Euro I to Euro I, but the emission levels of Euro I, Euro II and Euro III engines were rather similar over the total engine map. However, CO and HC are not critical pollutants for HDVs. For PM emissions, no data for the ECE R49 test for engines older than Euro I were available. A significant reduction in the emission levels over the ECE-R49 was observed from Euro I to Euro II. The tested Euro III engines had lower PM emissions over the corresponding type approval test (ESC) than the tested Euro II engines (ECE-R49). However, for the complete engine map (including the off-cycle points), the average PM emissions from the tested Euro III engines were only 14% lower than the average Euro II values, even though the emission limits had been reduced by one third.

These results clearly showed that the inclusion of a sufficient number of off-cycle test points in the ARTEMIS steady-state programme was a fundamental requirement for assessing the real-world emission behaviour of HDVs. Emission maps based solely on the ECE-R49 or ESC test would significantly underestimate emission levels for many engines, especially for NO_x.

The measurement campaign showed that HDV manufacturers design engines and vehicles for low fuel consumption and robustness at reasonable cost. Achieving a high fuel efficiency has a much higher market value than low real-world emissions. For a given engine the fuel efficiency can be increased (and PM emissions decreased) by earlier fuel injection, but the NO_x emission levels increase. The reason lies in the trade-off between fuel efficiency and NO_x emissions. Therefore, real-world emission levels depend very much on the design of the relevant type approval test, and not only on the emission limits. Hence, the old ECE-R49 test (which covered only a very small part of the engine operation under real-world conditions) was unable to guarantee low NO_x emissions for modern (post-1996) electronically-controlled engines.

A particularly positive finding of the work was that diesel engines up to Euro III proved to have very stable emission levels over their lifetimes. From in-use tests in the Netherlands (Riemersma, 2001; Rijkeboer *et al.*, 1998) and Germany (Motzkau, 2001), it was concluded that there was no increase in emissions with vehicle mileage.

Comparisons were also made between the emission behaviour of engines from Western and Eastern European manufacturers. In general, there was no indication that Eastern European engines have higher emission levels than their Western European counterparts. The potential influence of different conditions of service and inspection and maintenance for the Eastern European vehicles was not investigated. Since Eastern European Engines are not very common on European roads, they were not included in the model for determining emission factors.

Transient measurements

The ARTEMIS transient measurement programme consisted of the following cycles:

(i) ETC (European Transient Cycle).
(ii) ELR (European Load Response test).
(iii) Two TNO real-world cycles.
(iv) HBEFA test cycle, designed to cover different transient engine load patterns for model validation, rather than to reflect real-world engine loads.

Transient test results were available for 23 engines. A detailed description of the test programme is given by Hausberger *et al.* (2001). To assess the changes in emissions from Euro II to Euro III, the transient measurements of three Euro III engines and their corresponding Euro II predecessors were analysed in detail. The Euro III engines had around 3% higher fuel consumption compared with the Euro II engines. For NO_x, the Euro III engines showed reductions in emissions of up to 15%, and in some cases even a slight increase compared with the corresponding Euro II engines, depending on the test cycle. However, the emission factors calculated using PHEM – which were based on a much larger number of tested engines – clearly exhibited larger reductions from Euro II to Euro III. NO_x emissions measured over the ETC and HBEFA cycles were, on average, 10% lower for the Euro III engines than for the Euro II engines. This reduction was somewhat lower than expected, as the NO_x limit at type approval was reduced by 29% from Euro II to Euro III. The reduction in PM emissions from Euro II to Euro III showed a strong dependency on the manufacturer. The average PM emissions measured over the ETC and HBEFA cycles were broadly similar for Euro II and Euro III engines, even though the emission limits were reduced by 33% from Euro II to Euro III.

The data from the transient measurements were used mainly for the assessment of the effects of transient operation on emission behaviour, compared with steady-state conditions. When steady-state emission maps were used to calculate ‘quasi-steady-state’ emissions for transient cycles, large differences were observed between the calculated and measured emissions, especially for CO, HC and PM. The differences were assumed to be mainly a result of changes in combustion conditions (*e.g.* inlet pressure and temperature for turbocharged engines with intercooler). Other known potential inaccuracies, such as the interpolation routine and the repeatability of the measurements, are affected to a lesser degree. Recalculations, based solely on interpolation from steady-state engine maps, resulted in the underestimation of PM emissions over transient cycles of up to 50%. In general, Euro III engines showed less influence from transient conditions than Euro I and Euro II engines. This suggests a better application of these engines to changing conditions under transient load.

B5.2.3 Chassis dynamometer and on-board measurements

The chassis dynamometer tests were performed mainly for model development and evaluation purposes. Measurements were available for eight vehicles, five of which were tested according to the ARTEMIS protocol. For each of these five vehicles the engine was removed, tested on the engine test bed, and then re-fitted. The vehicle was then tested on the chassis dynamometer. The dynamometer test programme included nine different HBEFA driving cycles relating to a range of urban, rural and motorway driving conditions, and extensive measurements of relevant vehicle parameters (*e.g.* engine speed, temperatures and pressures of inlet air and outlet air, *etc*.). This enabled the whole sequence of model development to be performed, from steady-state emission maps and transient engine tests to the simulation of vehicle driving cycles. One HDV was instrumented with on-board measurement systems, and was simultaneously tested on the chassis dynamometer. Emissions were measured with 0% road gradient simulation. Additionally, emissions at various constant speeds were measured, whereby the vehicle speed and the driving resistances were adapted according to steady-state points measured on the engine test bed. This allowed an assessment to be made of the potential inaccuracies relating to different measurement systems and different boundary conditions compared with the tests on the engine test bed.

B5.2.4 Construction of the instantaneous model ‘PHEM’

Overview

The methodology for PHEM was selected following an extensive literature review and feasibility study by Hausberger (1998). The review noted that most HDV models employ similar methodologies to simulate engine torque and engine speed, with driving resistances and transmission losses being used to calculate the actual engine power, and transmission ratios and a gear-shift model being used to calculate the actual engine speed. All models use emission maps for the calculation of fuel consumption and emissions as function of torque/power and engine speed. Some models offer the user fixed driving cycles, whereas other models require speed-time profiles as an input. The influence of transient engine load (compared with steady-state load) on emission behaviour is taken into consideration in some models.

The models PHEM, Vehicle Motion Simulator, TNO HD Testcycles, VETO, ADVISOR and SEEK were included in a common procedure for model comparison and improvement in the COST 346 action. The model comparison was based on HDVs which had been measured on the chassis dynamometer, and whose engines had also been tested on the engine test bed. All tested models showed a good performance in the comparison (Rexeis *et al.*, 2006). Since the basic version of PHEM already included important features such as a gear shift model, standardised emission maps and a transient correction function, it was decided within ARTEMIS to further improve PHEM for the calculation of HDV emission factors. The data structure format for the engine tests was designed accordingly. As a result, of the models which were originally reviewed, only PHEM contains all the relevant data for the simulation of emission factors for average HDVs from pre-Euro I to Euro III, and for all vehicle size categories.

PHEM now takes the form of a computer-executable program with a user-friendly interface. It is optimised for simulating fuel consumption and emissions from HDV fleets, but can also be used for simulations of single vehicles as well as passenger cars. The outputs from the model are engine power, engine speed, fuel consumption and emissions of CO, CO_2, HC, NO_x and PM every second, as well as average values for the entire driving cycle. **Figure B5-3** illustrates the structure of the model.

PHEM is an instantaneous emission model in which fuel consumption and emission values are interpolated from steady-state engine emission maps for every second of a given driving cycle. For interpolating emissions from the engine map, the actual power demand from the engine and the engine speed are simulated according to the vehicle data given as model input. The simulation of the actual power demand of the engine is based on the driving resistances and the transmission losses, and engine speed is calculated using the transmission ratios and a gear-shift model. The different emission behaviour over transient cycles is taken into consideration by 'transient correction functions', which adjust the second-by-second emission values according to parameters describing the dynamics of the driving cycle.

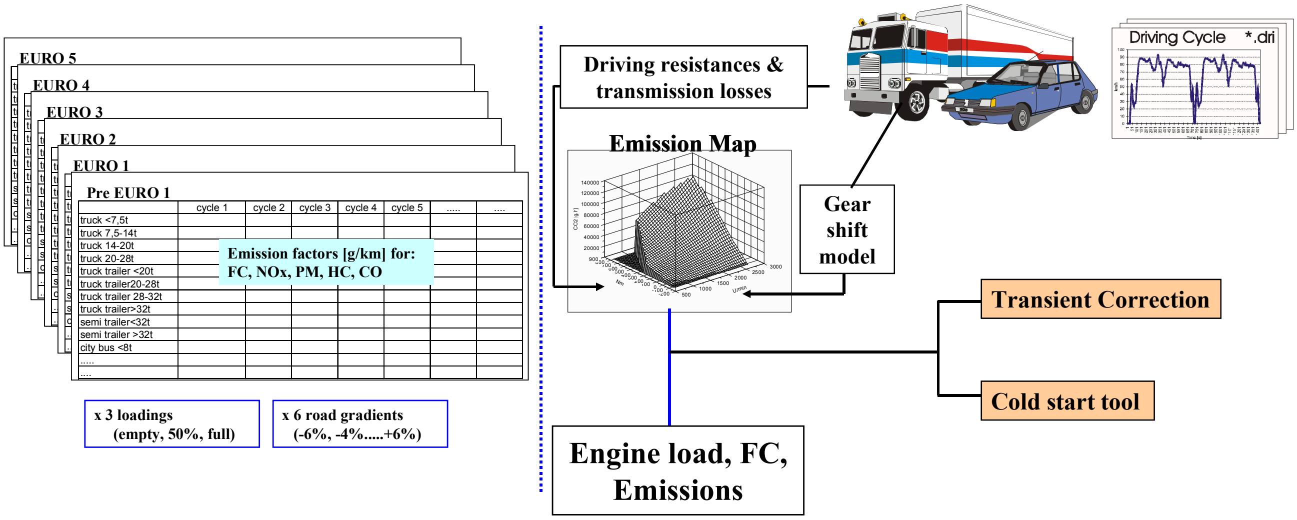


Figure B5-3: Structure of PHEM.

PHEM has some special features which were developed to enable the straightforward simulation of average HDV classes. For example, the input data are modular, with different files being used to describe the vehicle characterisation, the driving cycle, the engine emission map and the full-load curve. This enables a rapid simulation of various vehicle and driving cycle combinations. In the input file for the driving cycle, the measured engine speed or the gear position can be given as an optional model input. If neither the engine speed nor the gear position is given in the input file, PHEM uses a gear-shift model to simulate engine speed. When recalculating driving cycles measured on the chassis dynamometer, differences between simulated and measured emissions, which are related to differences in the gear-shift strategy, can be precisely addressed. This is a helpful tool for model development and model validation.

Engine power simulation

For a correct simulation of engine power, all driving resistances occurring during real-world operation have to be taken into consideration. In PHEM, the actual engine power (***P***) is calculated according to:

$$P = P_{rolling\ resistance} + P_{air\ resistance} + P_{acceleration} + P_{gradient} + P_{auxiliaries} + P_{transmission\ losses} \qquad \text{(Equation B5-1)}$$

The individual terms in the total power demand equation are calculated as described below.

Rolling resistance

The power for overcoming the rolling resistance is calculated in PHEM using the approach:

$$P_{rolling\ resistance} = m \cdot g \cdot (fr_0 + fr_1 \cdot v + fr_2 \cdot v^2 + fr_3 \cdot v^3 + fr_4 \cdot v^4) \cdot v \qquad \text{(Equation B5-2)}$$

where:
- $P_{rolling\ resistance}$ = power [W] to overcome rolling resistance
- m = mass of vehicle + load [kg]
- g = gravitational acceleration [m/s^2]
- $fr_0..fr_4$ = rolling resistance coefficients
- v = vehicle speed [m/s], the vehicle speed is computed as average speed of second i and second (i+1) from the given driving cycle. The corresponding acceleration is (v i+1 – vi).

Air resistance

The power for overcoming air resistance is calculated using the equation:

$$P_{air\ resistance} = C_d \times A_{Frontal} \times \frac{\rho}{2} \times v^3$$ (Equation B5-3)

where:
- $P_{air\ resistance}$ = power [W] to overcome air resistance
- C_d = drag coefficient [dimensionless]
- $A_{Frontal}$ = frontal area of the HDV [m^2]
- ρ = density of the air (on average 1.2 kg/m^3)

The values for C_d and $A_{Frontal}$ were taken from the specifications given by the manufacturer. If no manufacturer specifications for the C_d value were available, then C_d was set according to existing values for a similar HDV obtained from coast-down tests.

Vehicle acceleration

The model offers two options for the calculation of the power demand for vehicle acceleration. The more detailed option (option 1) simulates rotating masses as three blocks: wheels, gearbox, other rotating masses. If the moments of inertia are not known, a simplified method (option 2) is used.

Option 1:

To calculate the power required, the acceleration of the rotating masses is converted to the vehicle acceleration. This gives the following equation:

$$P_{acceleration} = (m_{vehicle} + m_{rot} + m_{loading}) \times a \times v$$ (Equation B5-4)

where:
- $P_{acceleration}$ = power [W] required to accelerate the vehicle
- a = acceleration of the vehicle [m/s^2]
- v = vehicle speed [m/s]
- m_{rot} = reduced mass for rotational accelerated parts =

$$m_{rot} = \frac{I_{wheels}}{r_{wheel}^2} + I_{mot} \times \left(\frac{i_{axle} \times i_{gear}}{r_{wheel}} \right)^2 + I_{transmission} \times \left(\frac{i_{axle}}{r_{wheel}} \right)^2$$ (Equation B5-5)

I = moment of inertia of the rotating masses [kg.m^2]

The wheels can be assumed to be cylinders (*i.e.* $I = m \cdot r^2/2$)

$$\frac{I_{wheels}}{r_{wheel}^2} = 0.5 \times m_{wheels}$$ (Equation B5-6)

m_{wheels} = mass of the vehicles wheels (including rims)

Option 2:

m_{rot} from the formula above is determined using a 'rotating-mass factor' Λ:

$$\Lambda(v) = \frac{m_{veh} + m_{rot}}{m_{veh}}$$ (Equation B5-7)

With this simplification, the power required for acceleration becomes:

$$P_{acceleration} = (m_{veh} \cdot \Lambda(v) + m_{loading}) \cdot a \cdot v$$ (Equation B5-8)

Λ is expressed as function of vehicle speed to take into account the influence of different transmission ratios and the resulting decreasing influence of angular acceleration of the engine and the gear box block with increasing vehicle speed.

$$\Lambda(v) = \Lambda_0 \cdot 0.833 \cdot [1 - 0.4 \cdot \log(v \cdot 0.0667)]$$ for 1m/s< v <12m/s (Equation B5-9)

Below 1m/s v is set equal to 1, above 12m/s v is set to a constant 12.0.

a	=	acceleration of the vehicle [m/s^2]
$m_{vehicle}$	=	mass of the vehicle (ready for driving) [kg]
$m_{loading}$	=	mass of the payload or the passengers and luggage [kg]
Λ_0	=	rotating mass factor, to be given as model input (~1.05 to 1.2)

The formula for Option 2 is derived from the more detailed simulation according to the model for Option 1.

For the first assessment of the actual power demand the simplified equation is always used, since the gear choice of the driver is modelled as a function of the actual power demand. Thus, the gear and the transmission ratios are not known at the first step of iteration.

Road gradient

The power for overcoming road gradients is calculated as[18]:

$$P_{gradient} = m \cdot g \cdot G \cdot 0.01 \cdot v \qquad \text{(Equation B5-10)}$$

where: $P_{gradient}$ = power [W] required to overcome the gradient
G = road gradient [%]
M = mass of the vehicle + loading [kg]

The road gradient has to be given as a model input value in the file containing the driving cycle on second-by-second basis.

Power demand of auxiliaries

The assessment of the HDV measurements on the chassis dynamometer suggested a rather constant power demand of auxiliaries from the tested vehicles. The power demand is therefore calculated in a simplified way:

$$P_{auxiliaries} = P_0 \cdot P_{rated} \qquad \text{(Equation B5-11)}$$

where: $P_{auxiliaries}$ = actual power [W] demand of auxiliaries
P_0 = power demand of the auxiliaries as ratio to the rated power [P_{rated}, dimensionless]

At present, this equation is adequate for ‘average’ HDVs. For special HDVs (*e.g.* waste disposal vehicles), a more detailed approach may improve the model accuracy.

Power demand of the transmission system

The power losses between the engine and the wheels are simulated as a function of the actual power, the engine speed and the transmission ratio. A simplified equation (Tieber, 1997) - based on transmission efficiencies - is used as a first approximation, since the gear choice of the driver is modelled as a function of the actual power demand. Thus, the gear and the transmission ratios are not known during the first iteration.

The transmission efficiency is defined here as:

$$\eta_{transmisson} = \frac{P_{dr}}{P_e} = \frac{P_e - P_{transmission}}{P_e} \qquad \text{(Equation B5-12)}$$

and $P_{transmission} = P_e - P_{dr}$ (Equation B5-13)

The simplified equations for the first approximation are:

$$\eta_{transmisson} = -6 \cdot \left(\frac{P_{dr}}{P_{rated}}\right)^2 + 2.7 \cdot \left(\frac{P_{dr}}{P_{rated}}\right) + 0.57 \quad \text{where } P_{dr}/P_{rated} < 0.2 \qquad \text{(Equation B5-14)}$$

$$\eta_{transmission} = -0.0561 \times \left(\frac{P_{dr}}{P_{rated}}\right)^2 + 0.1182 \cdot \left(\frac{P_{dr}}{P_{rated}}\right) + 0.8507 \quad \text{where } P_{dr}/P_{rated} > 0.2 \qquad \text{(Equation B5-15)}$$

The power losses in the transmission system are:

[18] This formula is based on the assumption that sin α ≈ tan α ≈ gradient, which is valid for the range of road gradients which are common for driving on paved roads (*e.g.* error of less than 2% for a road gradient of 20%).

$$P_{transmission} = \frac{P_{dr}}{\eta_{transmission}} - P_{dr}$$ (Equation B5-16)

where: P_{dr} = power to overcome the driving resistances (without transmission losses)

After the first estimate of the power losses in the transmission system (and after the first iteration of the power necessary for the acceleration of rotating masses) the next subroutine of PHEM is executed. This subroutine selects the actual gear using a gear-shift model. After the actual gear is determined, the losses in the transmission system are simulated according to the following method.

(a) Manual Gear box

The losses in the transmission system are directly calculated as power loss. The use of transmission efficiencies is avoided, since the transmission efficiency is near to zero for low-power transmission conditions. This would lead to a poorly defined value, since a low value for the engine power has to be divided by an efficiency near to zero. Following the basic method of PHEM, the formulae used are normalised to the rated power of the engine.

Power losses in the differential [kW]:

$$P_{Differential} = P_{rated} \cdot 0.0025 \cdot (-0.47 + 8.34 \cdot \frac{n_{wheel}}{n_{rated}} + 9.53 \cdot \text{ABS} \frac{P_{dr}}{P_{rated}})$$ (Equation B5-17)

where: P_{rated} = rated power of the engine

n_{wheel} = rotational speed of the wheels [rpm] = $n_{wheel} = \frac{60 \cdot v}{D_{wheel} \cdot \pi}$ (Equation B5-18)

P_{dr} = power demand from the engine to overcome the driving resistances (= total power demand without transmission losses)

Power losses in the gear box [kW]:

These losses are simulated for four transmission ratios. The losses for gears between these ratios are interpolated linearly. This method takes the characteristics from splitter-gear shifts – which are most common in HDV – into consideration, and was developed from measurements on a gear box.

$$P_{1.gear} = P_{rated} \cdot 0.0025 \times \left(-0.45 + 36.03 \cdot \frac{n_{engine}}{I_{1.gear}} + 14.97 \cdot \text{ABS}\left(P_{dr} + \frac{P_{Differential}}{P_{rated}} \right) \right)$$ (Equation B5-19)

$$P_{8.gear} = P_{rated} \cdot 0.0025 \cdot \left(-0.66 + 16.98 \times \frac{n_{engine}}{I_{8.gear}} + 5.33 \cdot \text{ABS}\left(P_{dr} + \frac{P_{Differential}}{P_{rated}} \right) \right)$$ (Equation B5-20)

$$P_{9.gear} = P_{rated} \cdot 0.0025 \cdot \left(-0.47 + 8.34 \cdot \frac{n_{engine}}{I_{9.gear}} + 9.53 \cdot \text{ABS}\left(P_{dr} + \frac{P_{Differential}}{P_{rated}} \right) \right)$$ (Equation B5-21)

$$P_{16.gear} = P_{rated} \cdot 0.0025 \cdot \left(-0.66 + 4.07 \cdot \frac{n_{engine}}{I_{16.gear}} + 0.000867 \cdot \text{ABS}\left(P_{dr} + \frac{P_{Differential}}{P_{rated}} \right) \right)$$ (Equation B5-22)

The total power losses in the transmission system are the sum of the losses in the differential and in the gear box. For the calibration of the absolute values a factor, A_0, is introduced. This factor can be set by the model user.

$$P_{transmission} = A_0 \cdot \left(P_{Differential} + P_{gear\,i} \right)$$ [kW] (Equation B5-23)

where: A_0 = factor for adjusting the losses (to be defined in the model input data, usually set to 1).

(b) Automatic gear box:

The power losses are simulated as a function of the vehicle speed according to Tieber (1997). Data permitting the development of a more detailed approach are not yet available.

$$\eta_{transmission} = 0.16 + 0.87 \cdot \left\{ (0.0001 \cdot v \cdot 3.6)^3 - 0.00213 \cdot (v \cdot 3.6)^2 + 0.084 \cdot v \cdot 3.6 \right\}$$ at $v < 5.56$ m/s

(Equation B5-24)

$\eta_{transmission} = 0.88$ at $v > 5.56$ m/s

(Equation B5-25)

The power losses in the transmission system are then given by:

$$P_{transmission} = \frac{P_{dr}}{\eta_{transmission}} - P_{dr}$$ (Equation B5-26)

where: P_{dr} = power to overcome the driving resistances (without transmission losses)

With the equations given in this Section the power demand from the engine can be simulated for any combination of vehicle, load, and driving cycle.

Engine speed simulation

The actual engine speed depends on the vehicle speed, the wheel diameter and the transmission ratio of the axis and the gear box:

$$n = v \cdot 60 \cdot i_{axle} \cdot i_{gear} \cdot \frac{1}{D_{wheel} \times \pi}$$ (Equation B5-27)

where:
- n = engine speed [rpm]
- v = vehicle speed [m/s]
- i_{axle} = transmission ratio of the axle [dimensionless]
- i_{gear} = transmission ratio of the actual gear [dimensionless]
- D_{wheel} = dynamic wheel diameter [m]

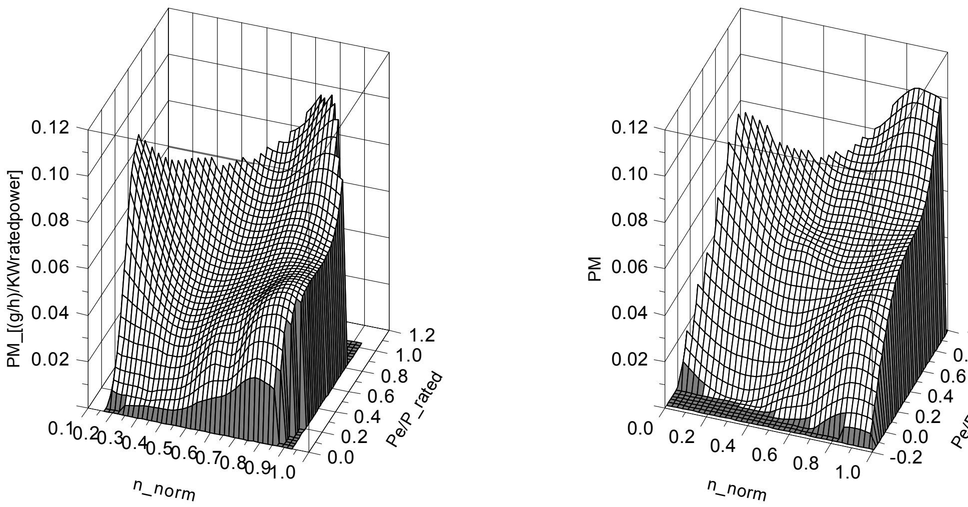
A given vehicle speed can achieved in any one of a number of different gears, and actual gear selection depends on a subjective assessment by the driver. Gear-shift behaviour is modelled in PHEM for three different types of driver: (i) ‘fast’, (ii) ‘economical’ and (iii) ‘average’. The basic assumption is that the ‘fast driver’ style is located in an engine speed range where high engine torque and high engine power are available, and that the ‘economical driver’ style is located in an engine speed range where the specific fuel consumption is the lowest for the given engine power demand. For these driving styles, engine speed limits are defined to determine when the gear has to be changed upwards or downwards. The ‘average driver’ is a mixture of styles (i) and (ii), and depends upon the engine power needed within the following seconds. Many checks and additional gear-shift rules are necessary to avoid erratic gear-shift behaviour in the model, with far too many gear-shift manoeuvres. The simulation routines for the different driving styles are described in detail by Rexeis *et al.* (2005). Of course, this modelling approach cannot simulate all gear changes exactly, especially for individual drivers. Nevertheless, comparisons have shown that the gear-shift model produces results which correspond well with measured gear-shift patterns, and leads to engine load distributions which are similar to those found in real-world traffic. As an alternative to the simulation of engine speed, the model allows the user to enter measured engine speeds or gear positions as input variables.

Normalisation of steady-state engine emission maps

A significant problem when modelling HDV emissions is having a sufficient number of measured engines in each fleet segment, since more than 100 segments of the fleet have to be covered. As each vehicle size class has typical values for rated engine power, each measured engine can be applied to only one fleet segment. To avoid a separation of the measured engines according to the rated engine power, the engine maps were normalised and brought into a standard format (a 40-point map). This enabled the development of average engine maps which were independent of engine size, and guaranteed that the single HDV fleet segments were covered by a proper number of measurements on different engines, and increased the number of engines available per fleet segment by approximately a factor of 10. The approach used is described in more detail in Rexeis *et al*. (2005). The model is able to handle almost any engine map format, and to convert it to the 40-point standard. The only requirement is that the units are adapted to the model standards.

Since all the measured engine maps showed no significant relationship between the emission level (in g/kWh) and the rated engine power, it was valid to create average emission maps for engines with different rated power. Exceptions to this were pre-Euro I engines, for which there was an increase in PM emissions with decreasing rated power. In the absence of type approval limits, smaller engines had, on average, cheaper and/or older technology. In particular, naturally aspirated engines had rather high levels of PM. For this reason, three average engine emission maps were derived for pre-Euro I engines. In order to avoid the further separation of the measured engine maps by engine size, the engine size dependency of specific fuel consumption is described in the model via correction functions.

Figure B5-4 shows an example of a PM emission map for a Euro II engine using all measured points, and the standardised PM map for this engine. Some of the ‘troughs’ at the type approval engine speeds, which can be seen in the map containing all measured points (left-hand picture), are not fully reproduced in the standardised engine map, since these engine speeds are not included. Due to the fact that the engine speeds of the type approval tests are located according to the individual full-load curves, and are therefore different for each engine, it is not possible to include type approval points in standardised maps in a way which is generally valid. Nevertheless, when calculating emissions for a complete transient cycle using all measured points, the results usually differ from those calculated using the standardised 40-point maps by less than 3%, since the points of the standardised engine map are average values from the nearest measured points. However, significant differences may be observed when modelling transient cycles which cover only small engine speed ranges and are located at, or near, the type approval engine speed range[19]. For the simulation of HDV emission factors the averaging effect of the standardised maps is beneficial. For some engines, when the original maps are used small differences in vehicle speed can result in very different emission factors. For purposes other than calculating emission factors, such as assessing emissions during specific cycles for a specific engine, the use of the original measured engine map is usually advantageous.



Measured *Standardised*

Figure B5-4: Comparison of the PM engine emission map from all measured values (52 points) and the standardised emission map (32 points) for a Euro II engine.

Since many countries have a very specific fleet composition with respect to engine manufacturers, it was of interest to determine whether the share of each manufacturer in the average engine emission map had a significant influence (Cornelis *et al.*, 2004). In this analysis the manufacturer and also the country of manufacture were not found to be strong determining factor in the emission behaviour of HDV engines. Hence, no distinction needs to be made between different engine manufacturers. As sample sizes were rather limited, the findings may not be representative for all the engines in Europe.

Transient correction functions

The engine emission maps were measured under steady-state conditions, whereas real-world driving behaviour almost always results in transient engine loads. In order to improve the accuracy of the model, the results of the calculations based on steady-state engine emission maps had to be corrected according to the dynamics of the cycle. Since transient engine tests were only available for one quarter of all engines, the method had to be generally valid, at least for all engines of the same technology.

The main problem in the development of dynamic correction functions is the identification of parameters which express the dynamic aspects of a cycle and also correlate well with the difference between measured emissions and the 'quasi-steady-state' emissions calculated for the transient cycle. For this purpose 'transient parameters', which showed good correlations with the transient emissions, were identified. For each single engine, multiple regression analysis was then used to determine relationships to describe the differences between the measured emissions over the transient cycles and the emissions calculated for these cycles from the normalised steady-state engine maps. The parameters giving similar equations for all engines were then filtered out. To increase the amount of data for the regression analysis, each transient test cycle was separated into 20-second sub-cycles using the modal measured emissions. This resulted in the following methodology for transient corrections:

$$\boldsymbol{E_{trans} = E_{QS} + P_{rated} \cdot F_{trans}} \qquad \text{(Equation B5-28)}$$

Where:
- E_{trans} = emission value under transient conditions [g/h]
- E_{QS} = quasi-steady-state emission value interpolated from steady-state emission map [g/h]
- P_{rated} = rated engine power [kW] (since emission values are normalised to the rated power)
- F_{trans} = dynamic correction function [(g/h)/kW rated power]

[19] Only relevant if the off-cycle emissions of the engine under consideration are clearly different to the emissions at the type approval points.

$$F_{trans} = A \cdot T_1 + B \cdot T_2 + C \cdot T_3$$ (Equation B5-29)

where: A, B, C = coefficients (different according to the exhaust gas component, but constant for one engine technology)
T_1, T_2, T_3 = transient parameters (calculated by PHEM from the engine speed and engine power cycles)

With this set of equations the accuracy of the simulation was improved for all engines over almost all cycles. **Figure B5-5** shows the results, using the transient correction function for eight Euro II engines and three Euro III engines. For each of these engines three to five transient cycles were measured.

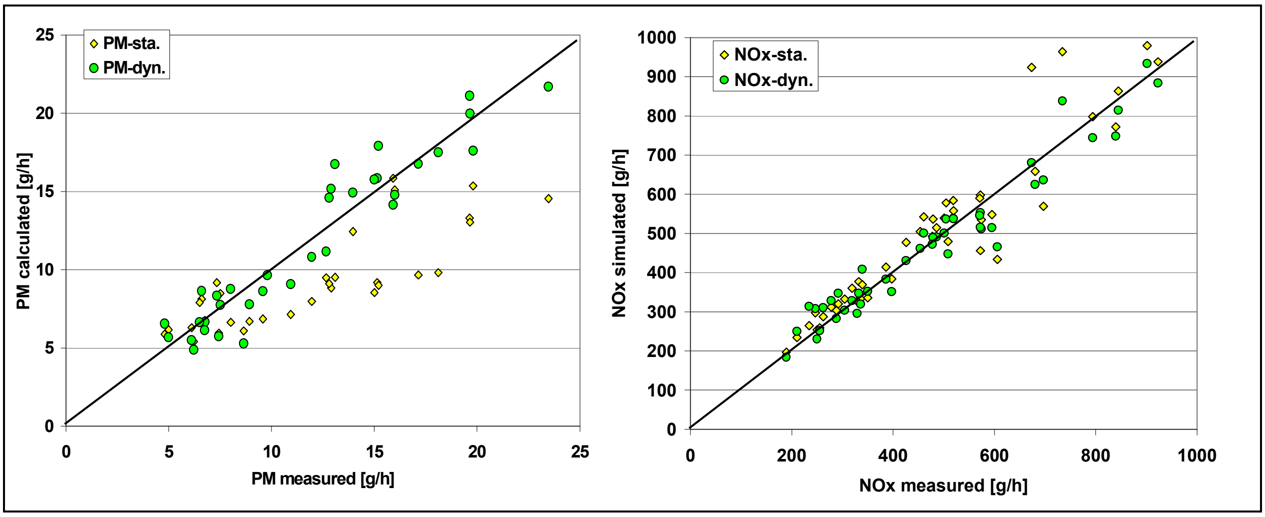


Figure B5-5: Comparison of simulated and measured particle and NO_x emissions with ('dyn') and without ('sta') transient correction function in the model.

Whilst PM emissions were underestimated when simply interpolated from the steady-state engine maps, the use of the transient correction resulted in better agreement with the measurements. For CO and HC similar results were achieved. For NO_x emissions the transient influences were small, and the transient correction function gave only slight improvements. For the aforementioned 20-second sub-cycles the transient correction function resulted in a deviation between simulated and measured emissions over transient engine test cycles of between ± 20% for NO_x, PM, CO and HC. Since the same function could be applied successfully to all engines within a technology class, a general valid method was found which could be used for the average engine emission maps in the normalised format.

As no measurements of engines from Euro IV onwards were available in ARTEMIS, and an accurate assessment of the transient behaviour of new technologies could not be made. The corresponding transient correction functions were therefore set to zero. Measurements conducted in 2006 on the first generation of Euro IV and Euro V engines with SCR-system (exhaust gas after treatment system for the reduction of NO_x emissions) showed a strong sensitivity of the NO_x emission level to transient and thermal conditions. However, the emission factors for Euro IV and Euro V should be updated as soon as a sufficient number of measurements is available. Such an update would also have to include the transient functions.

For PM, the low emission limits would not allow a significant increase under transient conditions compared with steady-state conditions. Even if the transient PM emissions in the raw exhaust gas increased, the effect would probably be reduced by the exhaust gas after-treatment system.

Estimation of emissions from Euro IV and Euro V vehicles

Euro IV was introduced in October 2005 for the type approval of new engine models. For Euro V the corresponding introduction date is October 2008. The assessment of the emission behaviour of engines meeting the Euro IV and Euro V standards is highly uncertain, as no production vehicles were available for measurement during ARTEMIS. Furthermore, the effects of the new technologies used to meet the type approval limits (*e.g.* SCR, particle oxidation catalysts) were difficult to predict. It was concluded from the measurement programme on Euro II and Euro III engines that simply extrapolating emission factors from older engine technologies to future standards according to the future emission limits is not a suitable approach. Compared with Euro III diesel engines, Euro IV and Euro V engines must also comply with the emission limits during the ETC. Consequently, optimisation at the single test points of the ESC will not be sufficient to meet the emission limits at type approval. With this regulation it can be assumed that emission levels during real-world driving conditions may decrease more compared with Euro III than the reduction in the emission limit suggests. However, most of the ETC is located in the same region of the engine map as the ESC. Thus, it will not be absolutely necessary for a manufacturer to optimise the emission levels over the complete engine map in order to meet the emission limits. In particular, low engine speeds are not often required; only 13% of the total ETC duration is driven with a normalised engine speed below 40% (n_{norm}).

The main issue relating to the determination of emission maps for Euro IV and Euro V engines was whether the technologies used would have a varying efficiency over the engine map. Potential technologies for Euro IV and Euro V engines are discussed below, but at present it cannot be foreseen which will dominate in the future. The actual effects applied in PHEM may be rather optimistic, since rational electronic engine control strategies and a restrictive OBD are assumed for all vehicles everywhere in the engine map. These assumptions are not reflected completely in the actual type approval Directive for Euro IV and Euro V. Most likely, emissions will drop clearly, but in-use tests seem to be necessary to prevent emission levels during real-world driving exceeding the type approval values significantly.

Emission control technologies

In general, three approaches for meeting the Euro IV and Euro V type approval limits will be available in the near future: improved engine technology, exhaust gas after-treatment and alternative combustion concepts. Whilst compliance with the Euro IV limits could be achieved with improved conventional engine technologies (fuel injection, exhaust gas recirculation, variable turbine geometry at the turbo charger, *etc.*), this is rather unlikely for Euro V. For example, the engine efficiency would be unacceptable for reaching the 2 g/kWh NO_x. Using exhaust gas after-treatment systems could reduce NO_x and PM to the targeted levels, but the problems with these systems are their unproven durability and the additional investment costs.

PM-reduction technologies

Various filter-based after-treatment systems are currently being developed to reduce PM emissions from HDVs – these are collectively known as diesel particulate filters (DPFs). For all these systems, the main technological challenges are controlled regeneration of the filter and durability. For the latter, the main challenge is the minimisation of the back-pressure increase due to cumulated ash stored in the filter. With or without delayed regeneration, the filter becomes blocked, and this rapidly increases the exhaust gas back-pressure. For current filter technologies using catalytic coatings or fuel-borne regeneration, temperatures above 300°C are necessary to initiate the filter regeneration process. Such temperatures do not occur under all load conditions for HDV engines. An overloading of only 3-4 grammes per litre of filter volume causes a rise in the regeneration temperature of 300-400°C. Such temperatures can damage the filter. Accumulated ash from lubricating oil additives will melt at high temperatures (>1100°C) during regeneration, and can react with the filter substrate and clog the filter permanently (glazing effect). Therefore, the loading rate and temperature of the filter have to be monitored accurately to prevent overheating and damage to the filter. Low-ash lubricants also have to be available for engines with DPFs. Solutions to these problems will most likely require the integration of a control system within the engine control unit. In addition to these technological challenges, particulate traps have additional investment costs, and result in a slight penalty in terms of fuel efficiency (1-3%). Therefore, research is under way to improve engine technology so that PM limit values can be met without the use of filters. The systems described below are examples of current developments.

- *Continuously-regenerating trap (CRT™, Johnson Matthey).* This technology uses the NO_x in the exhaust gas to continuously regenerate the trap. An oxidation catalyst is placed upstream of the filter to convert NO to NO_2. This process requires temperatures above 230°C to start the filter regeneration, and around 350°C to achieve equilibrium. For any category of HDV, driving situations can occur where this temperature is not reached. This leads to an accumulation of particles on the filter which are then burned off once the required temperature for regeneration is reached. Such conditions can damage the filter. Thus, additional systems for active regeneration may be needed.

- *Fuel-borne catalysed filter.* In this system, an additive is used to reduce the soot ignition temperature. The additive is introduced into the fuel tank after refuelling. The additives currently used are cerium, iron and strontium. The main disadvantage of this approach is the need for an additional tank for the additive. Malfunctions which are specific to this system are most likely to occur in the additive supply system. For example, too little dosing could lead to delayed regeneration and overheating during the regeneration process, as with the CRT system.

- *Diesel particulate catalyst.* Besides filter-based systems, in which the exhaust gas flows through a porous medium, ‘open’ systems have recently been developed. These systems are often called particulate catalysts or ‘PM-cat’. Due to the special shaping of the catalyst, the exhaust gas flows into a storage medium where particles are deposited. If the storage medium is full, the exhaust flows through the open channels of the catalyst without further separation of the particles. As soon as the PM-cat reaches the regeneration temperature, the particles are burnt off and the PM-cat can work at the original efficiency level. The risk of damage to the engine or to the PM-cat is obviously much smaller than for a DPF without closed-loop control. PM-cats have an efficiency of approximately 50%, and at least one HDV manufacturer is already applying this technology to smaller Euro IV vehicles.

NO_x-reduction technologies

There are currently two main approaches for reducing NO_x emissions: selective catalytic reduction (SCR), and exhaust gas re-circulation (EGR). An alternative after-treatment method - NO_x adsorption - requires the engine to be run periodically with a rich air to fuel ratio, which increases fuel consumption. As a consequence, SCR tends to be used in preference to NO_x

adsorption in HDV applications. No manufacturer is currently planning to introduce NO_x-adsorption technology in the European HDV market. SCR and EGR are described in more detail below.

- *Selective catalytic reduction.* In the SCR system, urea is dissolved in water and is injected into the exhaust gas stream, where a hydrolysis process converts it into CO_2 and NH_3. Alternatively, the NH_3 can be produced from ammonium carbonate. The ammonia is used as a NO_x-reducing agent, producing nitrogen and water in the catalyst. The SCR catalyst is a honeycomb structure made of ceramic material. To prevent ammonia from passing into atmosphere (ammonia slip) an oxidation catalyst is usually fitted downstream of the SCR catalyst. At normal exhaust gas temperatures, SCR is capable of reducing NO_x emissions by more than 65%. However, one of the drawbacks of current systems is that the SCR catalyst does not work at exhaust temperatures below 150°C. Consequently, the urea injection only begins at a defined temperature, and is controlled by a sensor. Engines running for a considerable period at idle may have problems reaching the required temperature, especially in winter. Additionally, after a cold start the system will not be active until the full operating temperature is reached. Another main concern is the level of urea in the storage tank. As there are no vehicle performance penalties when the reactant tank is empty, there is no incentive for the driver to replenish the tank. Monitoring of the urea level in the tank (as well as the chemical composition to avoid replenishing it with water) is therefore crucial for compliance.
- *Exhaust gas recirculation.* EGR is used to reduce NO_x emissions by recirculating a portion of the exhaust gas back into the combustion chamber. This reduces the oxygen available for combustion, and leads to lower peak temperatures, thus inhibiting the formation of NO_x. There are different principles of exhaust gas recirculation: (i) external high-pressure EGR, (ii) external low-pressure EGR and (iii) internal EGR. All of these options may be used in Euro IV and/or Euro V HDV engines. In high-pressure EGR the exhaust gas is forced back into the intake air manifold by the pressure in the exhaust manifold. The low-pressure EGR system re-routes the exhaust gas after the turbocharger and, if mounted, the particulate filter into the fresh airflow before the turbocharger. Apart from these external EGR systems, an overlapping opening of the exhaust and the intake valves can be used to obtain a mixture of fresh air and exhaust gas in the cylinder.

Effects on emission maps

High fuel efficiency is the main aim for HDV engine manufacturers, and is crucial for competitiveness in the sector. For Euro IV and Euro V vehicles, it must also be assumed that manufacturers will continue to focus on fuel efficiency for low investment and running costs. Consequently, the following assumptions were made for Euro IV and Euro V engines:

(i) Due to the technological disadvantages described above, it was assumed for the development of the basic emission maps that DPFs would not be widely used in Euro IV and Euro V engines. A reduction in PM emissions will be achieved via optimised fuel injection and combustion processes, in combination with an oxidation catalyst (or PM-cat), but without the application of a DPF. Available measurements from a Euro V SCR test engine[20] have shown PM emissions 40% lower than the Euro V limit value, over both the ESC and ETC cycles.

(ii) In the ARTEMIS model, the option of ‘DPF-technology’ can be chosen, which assumes a reduction in PM mass of approximately 90%, and an increase in fuel consumption of 3%, compared with the relevant basic engine emission map. This option may be helpful for assessing policies such as the introduction of DPFs in urban bus fleets.

(iii) For NO_x emissions, the basic technology for compliance with the Euro IV limits will be SCR. EGR with PM-cats will be applied mainly to some smaller vehicles. This slightly increases the fuel consumption factors for this fleet segment. The potentially different pollutant emission behaviour associated with SCR and EGR cannot be properly assessed at present. All Euro V HDVs will use SCR technology.

(iv) The application of SCR will be optimised in the regions of the engine map covered by the type approval tests (ETC and ESC). It is unlikely that emission-reduction strategies (*e.g.* urea dosing with SCR) will be applied to all regions of the engine map where there is no urgent requirement to do so, as this would imply penalties in terms of fuel consumption and cost. In addition, EGR may be operated with lower recirculation rates.

(v) OBD systems will be installed, limiting NO_x emissions everywhere on the engine map to 5 g/kWh for Euro IV and to 3.5 g/kWh for Euro V[21]. Without such control systems, especially at low engine speeds, much higher NO_x levels than currently indicated by the emission factors could emerge. This could drastically increase the emission factors for urban and rural driving. For this reason, the in-use control of future-technology vehicles seems to be necessary.

(vi) The application of the SCR system allows for higher raw exhaust NO_x emissions. This enables further optimisation of fuel consumption (earlier injection timing). Compared with Euro III engines, reductions of around 7% (for Euro IV engines) and 5% (Euro V engines) are predicted.

The reductions in emissions of NO_x and PM which are required to reach the Euro IV and Euro V limits are impressive. PM emissions will have to be reduced by approximately 70% to 90% compared with Euro III. The reductions in NO_x emissions

[20] Measurements of a Euro V test engine with SCR technology, and the corresponding basic Euro III engine, were made available from the PARTICULATES project.

[21] In the low-load engine map area, this limitation will probably not be practicable, because very low absolute NO_x emissions have to be detected by the OBD system.

to reach Euro V range from 50% to nearly 70%. The required technologies make the overall system much more complex. From an environmental point of view, a main question for the future is durability. Whilst current heavy-duty diesel engines show a rather constant emission level over their service lifetime, this may change with the introduction of much more complex systems.

Primary NO_2 emissions

The measurement of unregulated pollutants from HGVs was not explicitly included within the remit of the ARTEMIS project, but insight from a number of national programmes can be useful in characterising some of these sources. For example, with respect to European urban air pollution problems, it is the concentration of particulate matter and nitrogen dioxide that cause the most problems with respect to compliance with air quality limit values. Whilst the emissions of particulate matter were investigated within the ex-anti clustered project PARTICULATES, the measurement of oxides of nitrogen were restricted to total NO_X. As discussed in Section B3.3.2, the proportion of NO_X emitted as primary NO_2 has until recently been considered to be relatively low.

The principal recent source of HDV primary NO_2 data was the DfT-funded TRAMAQ project, undertaken by TRL and Millbrook (Latham *et al.,* 2004). Whilst this project was primarily charged with the investigation of the impact of traffic management on exhaust emissions, it included a series of measurements for primary NO_2. The fraction of primary NO_2 varied between 0% and 50%, though for 70% of vehicles the fraction was between around 8% and 18%. Full details of vehicle specifications used within this study are available in Latham *et al.* (2004). The fitting of a particulate trap may have implications for NO_2 emissions. For catalyst-based DPFs the catalytic action is achieved by oxidising a portion of the NO in the exhaust to NO_2, which is then used to aid oxidation of the soot collected in the filter. More recent measurements on buses being introduced into the London public transport fleet, are included in **Table B5-1** (AQEG, 2006). This clearly highlights relatively high primary NO_2 emissions associated with Euro III buses, but relatively low proportions for Euro IV buses.

Table B5-1: An extract from the Transport for London exhaust emission database, showing the proportion of primary NO_2, based on volumetric chemiluminescence data (AQEG, 2006).

Bus type	NO_X (g/km)	NO_2 (% of NO_X)
Euro III buses fitted with DPF		
Volvo B7TL Double Deck	12.42	53.4
Scania Double Deck	10.58	39.3
Optare Solo Single Deck	5.43	24.3
Mercedes-Benz Citaro G Artic	12.98	35.0
Euro III buses fitted with DPF and SCR		
Dennis Dart single deck	5.33	46.0
Dennis Dart single deck	4.89	54.3
Euro IV buses without DPF		
Dennis Enviro 400 double deck	7.26	3.7
Dennis Dart single deck	8.6	7.7

Whilst the existing exhaust emission legislation has sought step-wise reductions in NO_X mass emissions, the changing proportion of primary NO_2 emissions associated with new engine and exhaust after-treatment technologies raises the potential need to control primary NO_2 emissions. The California Air Resources Board (CARB) undertook a consultation exercise in March 2006 to seek the adoption of proposed amendments to the Verification Procedure, Warranty and In-Use Compliance Requirements for In-Use Strategies to Control Emissions from Diesel Engines. The proposed amendments included a revised limit on emissions of NO_2, which are currently suspended[22]. The proposal re-defined the NO_2 limit, expressing it as an emissions increase associated with the verified control technology (as opposed to an absolute NO_2 level). The proposal set an NO_2 limit of 30% (relative to the baseline NO_X) which would become effective in January 2007. From 2009, the NO_2 limit would be further tightened to 20%. The proposal also included new preconditioning requirements for technologies, where NO_2 emissions may be influenced by the presence of soot and/or ash.

B5.3 Generation of emission factor database for traffic situation model

The ARTEMIS emission factor database for conventional diesel HDVs was compiled using PHEM. The objective was to obtain plausible average vehicle specifications for each single vehicle category and traffic situation in the model (see Section B2). The model was run to generate fuel consumption values and emission factors (CO, THC, NO_x and PM) using vehicle and engine data for the 'average HDVs' and representative driving cycles, and this resulted in the production of emission factors (all pollutants and fuel consumption) for almost 170,000 combinations of vehicle category (and Euro class), driving

[22] In 2002, CARB developed a verification procedure for diesel exhaust after-treatment retrofits. This set a primary NO_2 limit of 20% of the total baseline NO_x. This limit proved too restrictive, and in 2004, was suspended for a period of 3-years. For more information on this ruling, see http://www.arb.ca.gov/regact/verpro06/verpro06.htm

cycle, vehicle load and road gradient. It is not possible to list all the simulation results in this Report. The results are available in the electronic database of the ARTEMIS inventory model.

As a first step, the different vehicle specifications needed for the model input (*e.g.* masses, driving resistances, power losses) were investigated by analysis of statistical data, literature review and vehicle measurement. In order to harmonise the model input data for all vehicles, the data for the Euro III vehicle generation were defined, and for all other Euro classes, the model input data were then determined through the application of scaling factors to the Euro III vehicle specifications. As a second step, a 'calibration' of the assembled sets of vehicle data for the different vehicle categories was performed by a comparison of the fuel consumption predicted by PHEM with data from on-road measurements, test reports in technical journals, communication with transport businesses, and the TUG database.

The structure of the HDV emission factor database reflects that of the ARTEMIS road transport model. The three main heavy-duty vehicle categories defined in the model are 'heavy goods vehicles', 'coaches' and 'urban buses'. These are then further divided into sub-groups according to type and mass. At the most detailed level in the ARTEMIS model the sub-groups are divided into emission classes, which are termed 'sub-segments'. The emission classes included are pre-Euro I, Euro I, Euro II, Euro III, Euro IV and Euro V. In order to generate the emission factor database a large number of pre-defined driving cycles were entered into the PHEM model. These pre-defined cycles were specific to given vehicle categories. However, the PHEM model adjusts the driving cycle, and reduces the cycle speed profile if it can not be followed with the given engine power performance. Consequently, the actual driving cycles used were individually distinctive, and varied according to the vehicle category, the gradient and the vehicle load. Therefore, it is not possible to describe all the cycles in detail here. Three levels of vehicle load are taken into consideration: 0%, 50% and 100%, and seven gradient classes are included in the database: -6%, -4%, -2%, 0%, +2%, +4% and +6%.

B5.4 Average-speed emission functions

B5.4.1 Data extraction

The HDV emission factor database was also used to determine average-speed emission functions for HDVs (Boulter and Barlow, 2005). For each combination of gradient and vehicle load the speed and emissions data for the 114 vehicle sub-segments were extracted. For each vehicle load at 0% gradient, the data file contained 17,616 rows (*i.e.* combinations of sub-segment and driving pattern). This meant that the average speed-emission curve for a given sub-segment and load at 0% gradient contained around 150 data points. For gradients other than 0% the number of data points was 6,492, equivalent to an average of around 60 data points per sub-segment.

B5.4.2 Curve fitting

For each combination of sub-segment, gradient, vehicle load and pollutant, a regression curve was fitted to the emission data, describing the emission factor (g/km) as a function of average trip speed. To each set of data, 16 different regression models were applied, and the model giving the highest R^2 value was automatically selected. All models generally provided an exceedingly good fit to the data, with the linear R^2 value normally being greater than 0.90. **Figure B5-6** shows a typical example. This process led to the derivation of 11,970 average speed emission functions - as the product of 114 vehicle sub-segments, 5 pollutants (including fuel consumption), 7 gradients and 3 vehicle loads. Again, these are provided in the ARTEMIS model, and are available separately in electronic form. Examples of the functions, showing the effects of gradient, are given in **Figure B5-7**.

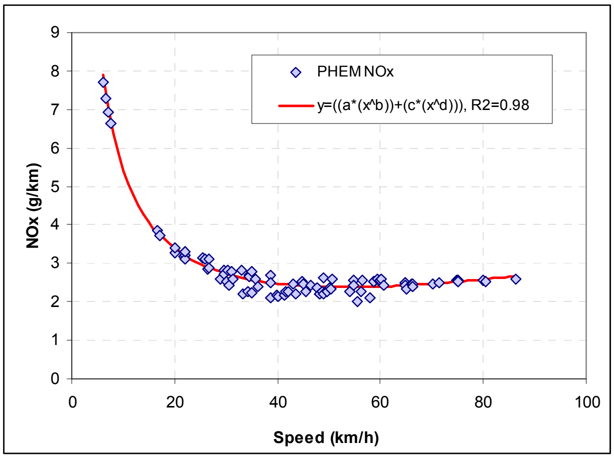


Figure B5-6: Regression fit to the data for a rigid truck <=7.5t, Euro III. Two-power-fits model, R^2=0.98.

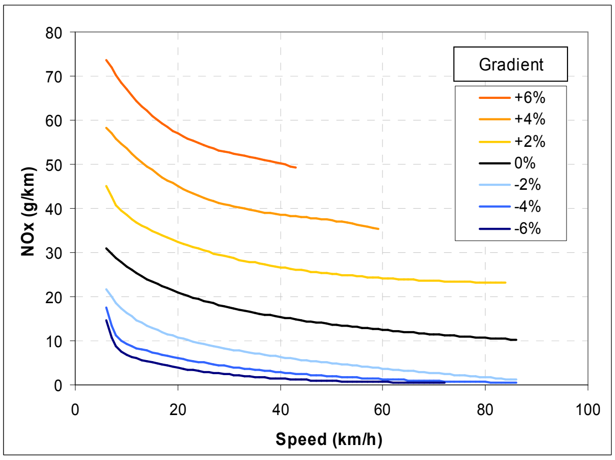


Figure B5-7: Effect of gradient on NO_x emissions at 50% load. Truck-trailer/artic. truck 50-60t, Euro II.

B5.5 Other modelling considerations

B5.5.1 Effects of fuel quality on emissions

An approach was proposed for including fuel quality effects in the ARTEMIS model (Rexeis *et al*., 2005 and references therein), whereby a percentage change in emissions is applied to the basic emission factors. This approach required a baseline fuel to be defined, from which changes could be evaluated. Baseline fuel properties for pre-Euro I, Euro I and Euro II engines were taken from the Worldwide Diesel Fuel Quality Surveys. Baseline fuel properties for Euro III engines were defined based on the average quality of the corresponding fuels used in the ARTEMIS tests. Baseline fuel properties for Euro IV and Euro V generations were estimated based on the requirements of vehicle and engine manufacturers, as published in the latest World–Wide Fuel Charter. The proposed baseline fuel properties are summarised in **Table B5-2**.

Table B5-2: Baseline fuel properties (Rexeis *et al*., 2005).

Emission legislation	Density (kg/m^3)	Cetane number	Cetane difference	Poly-aromatics (%)	Total aromatics (%)	T10 (^{o}C)	T50 (^{o}C)	T95 (^{o}C)	Sulphur Content (ppm)	Oxygen content (%m)
Pre-Euro1	835	51	0	6	25	205	260	345	1500	0
Euro I	835	51	0	6	25	205	260	340	1300	0
Euro II	830	53	0	5	20	205	260	340	300	0
Euro III	830	53	0	4	20	210	265	340	40	0
Euro IV	830	55	0	2	15	210	265	340	10	0
Euro V	830	55	0	2	15	210	265	340	5	0

The percentage changes in emissions were calculated using the models described below. This percentage could then be applied as a change to the emission factors estimated by the main model, based on the baseline fuels.

According to Rexeis *et al*. (2005) the most comprehensive investigations of the effects of fuel properties on HDV emissions have been carried out within the scope of the following programmes

- European programme on emissions, fuels and engine technology, 1995 (EPEFE).
- USEPA heavy-duty engine working group programme2000 (EPA-HDEWG).
- US diesel emission control – sulphur effects programme(DECSE 1999a,b; 2000a,b).
- EPA project on modelling effects of diesel fuel properties on HDDE emissions, USA, 2001 (new EPA).

Rexeis *et al*. (2005) recommended the use of the following models:

- The EPEFE model for assessment of fuel effects on CO and PM emissions.
- The New EPA model for assessment of fuel effects on HC and NO_x emissions.

The forms of these models are shown in **Table B5-3**.

Table B5-3: EPEFE and new EPA regression equations.

Pollutant	EPEFE [g/kWh]	New EPA, [g/hp h]
CO =	2.24407-0.00111***D***+0.00007***P***-0.00768***C***-0.00087***T95***	
HC =		Exp(5.32059-0.1875***CN***+0.001571***CN***^{2}-0.0009809***T10***-0.002448***T50***-0.1880***CD***+0.003507***CN********CD***)
NO_x =		Exp(0.50628-0.002779***CD***+0.002922***A***+1.3966***G***-0.0004023***T50***)
PM =	(0.06959+0.00006***D***+0.00065***P***-0.00001***C***)*[1-0.000086(450-***S***)]	

D – density, kg/m^3; ***G*** – specific gravity; ***P*** – poly-aromatics content, % m; ***A*** – total aromatics content, % vol; ***C*** – cetane number; ***CN*** – natural cetane number; ***CD*** – cetane difference due to additizing; ***S*** – sulphur content, ppm; ***T10*** – T10 temperature, ^{o}F; ***T50*** – T50 temperature, ^{o}F; ***T95*** – T95 temperature, ^{o}C.

B5.5.2 Effects of engine deterioration and maintenance

Emissions of HDVs are influenced by a large number of factors. Apart from obvious factors such as usage conditions, engine design and engine technology (to comply with emission legislation), the age of the engine and the maintenance condition can affect emissions. In order to determine whether such effects had to be taken into account in the ARTEMIS model, the effects of engine deterioration and maintenance on emissions were assessed. For investigating the influence of engine deterioration and maintenance on emissions, extensive data on pre-Euro I to Euro III vehicles from the Dutch and German in-use compliance programmes were used. However, for engine deterioration the work showed that no corrections to the emission factors for any Euro class were required.

For Euro I and Euro II vehicles it is assumed that maintenance would result in the changes shown in **Table B5-4**. The overall effect was calculated by multiplying the percentage of vehicles needing maintenance by the average reduction in emissions imposed by applying the necessary maintenance. The reductions were weighted for potential differences in fuel consumption as a result of maintenance, since this would have had a secondary influence on the emission level during the tests.

Table B5-4: Average emission effects (% change) as a result of maintenance activities, and the expected overall effect on average Euro I and Euro II fleet.

Percentage of vehicles needing maintenance	Euro I	Euro II
	52%	33%
Average effect on PM	-15%	-23%
Average effect on NO_x	-3%	-2%
Average effect on CO	-17%	-4%
Average effect on HC	2%	-11%
Overall effect on PM	-8%	-7%
Overall effect on NO_x	-1%	-1%
Overall effect on CO	-9%	-1%
Overall effect on HC	1%	-4%

For Euro III technology vehicles equipped with electronic fuel pumps and an engine management system, the condition of the fuel injectors can be expected to be the main issue. However, this has not been substantiated by recent ARTEMIS measurements on Euro III vehicles, in which none of the 24 vehicles tested had injector problems. On the other hand, these vehicles were relatively new, with odometer readings not exceeding 180,000 km. Based on the Euro II data, around 20% of the vehicles had problems relating to the injectors, resulting in an average PM increase of around 18%. Over the vehicle fleet this equates to an average increase of 3-4% for Euro II vehicles, and probably less for Euro III vehicles. For the other pollutants, the increase in emissions from Euro III vehicles is likely to be insignificant (Rexeis *et al*., 2005).

B5.5.3 Emission factors for alternative engine concepts

Alternative engine concepts, such as natural gas engines, have volumes of production which are much lower than those of diesel engines, and were therefore not included in the ARTEMIS measurement campaign. Emission factors for alternative concepts therefore had to be estimated from the available literature. Currently, the only alternative fuels that have reached appreciable shares of the HDV market are bio-diesel, compressed natural gas (CNG) and liquefied petroleum gas (LPG). Other concepts, such as hybrid vehicles, are only available in small numbers and so no reliable emission measurements are yet available. Also, for modern LPG-fuelled HDVs, no satisfactory data on emission levels were found, so no emission factors could be provided (Rexeis *et al*., 2005).

Compressed natural gas (CNG)

Compressed natural gas is used in SI engines with special fuel injection. Early CNG engines were operated almost exclusively stoichiometrically, and with controlled 3-way catalysts. This concept was able to reach very low emission levels for NO_x, CO, HC and PM, at least when new. Durability tests for modern vehicles are not commonly available, and some early examples showed a poor emission stability over time. A main disadvantage of this concept is the much lower fuel efficiency compared with diesel engines. Energy consumption from stoichiometric CNG engines is at least 10% higher than that for diesel HDVs. For part load conditions, this disadvantage may rise to 20% or more.

For this reason, several modern CNG buses are equipped with lean-burn engines, a technology offering benefits in fuel efficiency compared with the stoichiometric SI engine. A disadvantage of the lean-burn engine is that the catalytic converter does not reduce NO_x emissions during lean-burn conditions. Thus, as with diesel engines, the same principle trade-off between NO_x and fuel efficiency occurs. Therefore, the use of CNG does not necessarily provide benefits in terms of NO_x emissions level. The potential of CNG to reduce emissions depends heavily upon the application of the electronic engine management system and the compromise between fuel efficiency and low emissions in real-world driving.

Table B5-5 summarises the emission levels of modern CNG engines as a percentage of the Euro III emission factors. Since individual vehicles, both diesel and to a greater extent CNG, can show large differences in emission levels, the results have to be seen as best current indications of the average changes to be expected. Compared with Euro IV and Euro V diesel engines the advantages of CNG would diminish, since the Euro IV and Euro V limits require clear reductions in NO_x and PM emission levels. Of course, further emission reductions could also be achieved for CNG vehicles (Rexeis *et al.*, 2005).

Table B5-5: Emission levels of a CNG-fuelled HDV relative to the emission factors for a Euro III HDV (ratios based on real-world cycles; [g/km] for emission and fuel consumption values).

Technology	NO_x	PM	CO	THC	NMHC	FC
Diesel Euro III	100%	100%	100%	100%	100%	100%
CNG EEV *a*	85%	10%	15%	300%	25%	120%

a Enhanced Environmental Friendly Vehicle with lean burn concept. Note: measured emissions from a single CNG-fuelled HDV differ significantly from the values given here, depending on the manufacturer, the mileage and the test cycle.

Bio-diesel

For the HDV sector, compliance with the European Biofuels Directive – stating that a 5.75% share of the fuel used in 2010 must be biofuel – may, to a large extent, be realised by the use of bio-diesel. If the existing Directives on fuel quality are met (ÖNORM C1190, DIN-Norm 51606, EN 14214, EN 590), bio-diesel can be used in many HDVs without major modification, as long as important criteria for the storage of bio-diesel and the method for replacement of fossil diesel are considered. While the blending of up to 5% bio-diesel does not affect emission levels very much, the use of pure bio-diesel certainly has an effect on the emission behaviour of diesel engines. Measurements indicated an increase in NO_x emissions of 10-20%, but reduced PM emissions (although for some vehicles and test cycle an increase in PM was observed).

Also, the source of bio-diesel (vegetable oil from rape seed, palm, soybean, used cooking oil, animal fat from tallow, *etc*.) influences the emission changes resulting from fossil fuel being substituted by bio-diesel. Therefore, the emission changes associated with a shift from fossil diesel to bio-diesel given in **Table B5-6** have to be seen as average estimates.

Table B5-6: Emission levels of HDVs driven with bio-diesel instead of fossil diesel (ratios based on g/km emission and fuel consumption values).

Fuel	NO_x	PM	CO	THC	NMHC	FC
Conventional diesel (Euro III)	100%	100%	100%	100%	100%	100%
Bio diesel *a*	120%	80%	75%	60%	50%	115%

a Average ratios if fossil diesel is replaced by bio-diesel (RME or FAME). Note: single measured results differed by more than 15% from the values given here, depending on the vehicle, the bio-diesel and the test cycle.

B5.6 Model Validation

The validity of the PHEM emission factors in real-world situations was investigated via comparisons with chassis dynamometer and on-road emission measurements (validation of the simulation results for single vehicles) and tunnel measurements (validation of the results for the emission level of the vehicle fleet).

B5.6.1 Chassis dynamometer tests

Four individual HDVs were measured over real-world driving cycles on the chassis dynamometer, and the results were compared with the PHEM predictions. In a first step, for three of the four measured HDVs the engine was removed from the vehicle and placed on the engine test bed for measurement over the full ARTEMIS test programme (steady-state map, including off-cycle points and transient tests). Then, the engine was remounted in the vehicle for the emission test on the chassis dynamometer. For one of the vehicles, the engine map also had to be measured on the chassis dynamometer, as the owner did not allow the engine to be removed. For the validation of PHEM, the emissions were then calculated using the 40-point standardised engine emission map and the full-load curve from the actual HDV, the average transient correction function for the relevant Euro category, the gear-shift model settings, and the measured vehicle speed curve from the chassis dynamometer. All relevant vehicle parameters in the PHEM input data file were set according to the manufacturer specifications or measured values. The rolling resistance coefficients and the drag coefficient were derived from coast-down tests on the road. The value for $\boldsymbol{P_0}$ (power demand from auxiliaries) was set to a standard value. Overall, the only variable parameter for the simulation was $\boldsymbol{P_0}$, which was determined to be between 2% and 3.5% of the rated power for all simulated

HDVs by comparing the fuel consumption of the model with the measurement. As sensitivity tests for $\boldsymbol{P_0}$ showed close agreement for all HDVs, the average value of $\boldsymbol{P_0}$ from these HDVs was set to 2.5% in the final simulation.

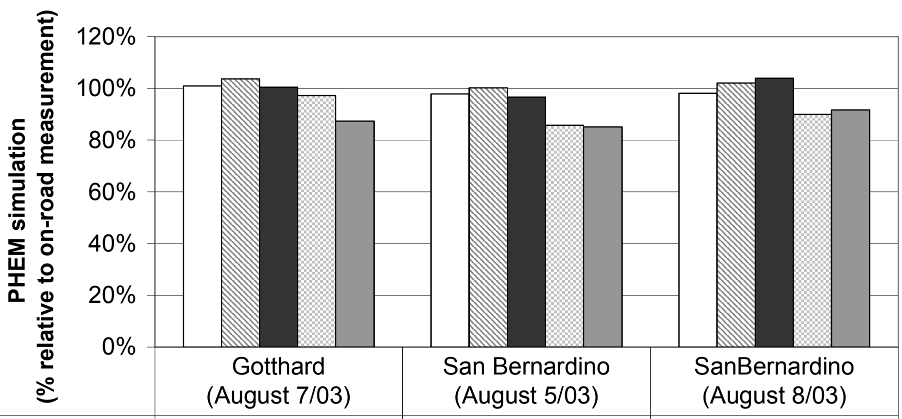
The fuel consumption values were simulated quite accurately, with the highest deviation for an individual vehicle being +13%. However, the engine of the HDV having the largest deviation obviously used a more economical control strategy over transient cycles than during the steady-state tests, and NO_x emissions were underestimated by up to 30% when using the 'average' transient correction function for Euro III engines. The fuel consumption values simulated for the other HDVs were within -10% and +14% of the measured values. In general, the deviations between the measured and predicted values were approximately double the deviations observed during the simulations of the engine tests. NO_x emissions were simulated to within ±25% of the measured values. For comparison, the engine tests were simulated to within ±15% for NO_x. The deviations for the HC and CO emission predictions were of the same order of magnitude as those observed for the engine tests. The deviation for HC was between –30% and +50%. Again, the simulation of the CO emissions from a single HDV was very inaccurate (-40% to +100% deviation).

The accuracy of the simulation for the total vehicle was somewhat lower than that for the simulation of the engine alone. But this was in accordance with expectations, due to the fact that the engine power demand and the engine speed have to be simulated for the calculation of HDV driving cycles. For PM emissions the deviations between the measurements and the simulations of the single vehicles were between ±50%, and therefore worse than those on the engine test bed. For the average of the vehicles, the differences between measurement and simulation were between ±15%. This level accuracy for the PM emissions of the 'average' HDV was similar to the results found on the engine test bed. Although a direct comparison with the findings of the engine test simulation was not possible due to the limited number of HDVs tested on the chassis dynamometer, the results suggest that the accuracy decreased by 2.5% for fuel consumption, and by 5% to 10% for the pollutant emissions when simulating the total HDV instead of simulating engine tests. However, the model accuracy was still acceptable

B5.6.2 On-road measurements

A tractor-semitrailer with a kerb weight of 40 tonnes was used for an on-road measurement campaign (Soltic and Hausberger, 2004). The concentrations of several gaseous pollutants, mass flows, pressures, temperatures, engine speed and torque were measured during trans-alpine driving across Switzerland. After the on-road measurements, the engine was removed from the vehicle and measured on a test bed over several cycles. The laboratory and on-road measurement equipment were operated in parallel. For the calculations with PHEM, the standard vehicle parameters (*e.g.* the driving resistances) for an average tractor-semitrailer of 34-40 tonnes maximum allowed gross weight were used as input. Some vehicle-specific data were replaced by the values for the tested vehicle. These included the engine emission maps with transient correction functions (gained from the engine test bed measurements), the transmission ratios of the gearbox, and the total vehicle mass. The measured on-road vehicle speed and road gradient were used as model inputs. A brief summary of the results is given in **Figure B5-8**. The simulation of the required engine work, based on the vehicle specifications and the trip data (vehicle speed and road gradient), matched the measured values almost exactly (deviations of 0% to 4%). The measured and simulated values for fuel consumption agreed to within ±2%, and NO_x emissions were underestimated by the model by between 0% to 4%. The predicted THC and CO emissions differed from the measured values by –3% to –15%[23]. Based on these on-road measurements, it was concluded that the simulated fuel consumption and emissions matched the measured on-road values very well.

[23] The on-road measurement campaign focused on gaseous emissions. On-road particle emission data would also be of significant interest.



	Gotthard (August 7/03)	San Bernardino (August 5/03)	SanBernardino (August 8/03)
fuel mass	101%	98%	98%
engine work	104%	100%	102%
NOx mass	100%	97%	104%
THC mass	97%	86%	90%
CO mass	87%	85%	92%

Figure B5-8: Comparison of model predictions and on-road measurements.

B5.6.3 Road tunnel measurements

The validity of the emission factors under real-world conditions was also investigated using tunnel measurements (more detail on this approach is given in Section B9). Measurements were performed in the Plabutsch tunnel in November 2001. The tunnel, which is on the A9 motorway, serves as a by-pass for the City of Graz, Austria. It is a 10 km-long one-bore tunnel with two lanes (operated with counter-flow). It is divided into five ventilation sections, and is operated with a transverse ventilation system. The sampling site was located 4 km inside the tunnel, in the middle of ventilation section 3 where a homogeneous mixture of air and pollutants could be assumed. Air quality monitoring equipment was installed in a lay-by within the ventilation section. The road gradient in this section was ±1%. The measurements were analysed using a regression approach. Based on this analysis, estimated emission factors for passenger cars and heavy-duty vehicles could be derived for each driving direction (*i.e.* in this case ±1% road gradient).

The emissions measured in the ventilation section were also calculated using PHEM. Assumptions of the loading conditions and the fleet composition were necessary, since this information was not available from the monitoring of the traffic flow. The data on the HDV fleet composition was taken from the Handbook of Emission Factors (Hausberger *et al*., 2003). The emission factors for the Plabutschtunnel were simulated in three different ways:

(i) Using the version of HBEFA which was current at the time (version 1.2).

(ii) Using PHEM with the driving cycles from HBEFA 1.2.

(iii) Using PHEM with driving cycles recorded in the Plabutschtunnel (in the aforementioned part of the tunnel, with separate cycles for +1% and -1% road gradient).

The driving cycles already available in the HBEFA were used to interpolate the emission factors for +1% and -1% road gradients. This approach is in accordance with that used in the updated HBEFA (Version 2.1). The emission factors obtained from these calculations were corrected with regard to the ambient conditions in the tunnel, which promoted the generation of NO_x (lack of humidity, higher temperature). The correction was performed according to the EC type approval regulations, and the results are shown in **Table B5-7**. As expected, HBEFA 1.2 showed a clear under-estimation of the NO_x emission level. The second validation step, using PHEM, showed higher NO_x values for the same driving cycle as that used in HBEFA 1.2, but the measured emission level was still not reached. Since the driving cycles in HBEFA give the road gradient in steps of 2%, the emission factor for ±1% gradient had to be determined by means of linear interpolation. The influence of gradient, loading and driving cycle on the emission level of heavy-duty vehicles is remarkably high, and often non-linear. In a third step PHEM was used with a driving cycle measured in the Plabutsch tunnel and the actual road gradients (‘PHEM+Plabutsch-Cycle’). The results of this simulation agreed closely with the emission factors obtained from the road tunnel measurements. A detailed description can be found in Hausberger *et al.* (2003).

Table B5-7: Emission factors obtained by tunnel measurements and by calculation.

Emission factors NO_x (g/km)		Measurement Nov 2001	Simulation		
			HBEFA 1.2	PHEM + HBEFA cycle	PHEM + Plabutsch cycle
Road gradient +1%	Basis		10.48	12.46	13.39
	Correction for ambient conditions		1.01	1.20	1.29
	Result	14.9	11.50	13.66	14.69
Road gradient -1%	Basis		6.19	6.61	8.95
	Correction for ambient conditions		0.60	0.64	0.86
	Result	9.98	6.78	7.25	9.81

The results indicated that PHEM, comprising the input data for delivering fleet emission factors, is quite accurate for predicting the emissions of HDVs in any traffic situation. The highest accuracy can be reached with a simulation of driving cycles measured exactly for the traffic situation under consideration. Using the emission factors prepared for ARTEMIS and for the HBEFA 2.1 saves the effort of measuring driving behaviour and extra simulation runs with PHEM, but can increase the error since it is not possible to cover all potential real-world traffic situations with pre-defined driving cycles.

B5.7 Results and discussion

As the major output of the HDV part of the ARTEMIS project, emission factors for 170,000 combinations of vehicle category, Euro class, vehicle load, driving cycle and road gradient were simulated using PHEM. The principal results are summarised here for single vehicle categories in order to demonstrate the influence of emission legislation and driving cycles on emission behaviour. The results should only be viewed as examples, since they are often different for other combinations of vehicle category, vehicle load and road gradient. **Figure B5-9** and **Figure B5-10** show the modelled fuel consumption and NO_x emission factors for truck trailers/articulated trucks with a maximum allowed gross weight of 34-40 tonnes. Fuel consumption decreased from pre-Euro I to Euro II by more than 15% on average over all cycles. The more stringent NO_x limits and the broader controlled engine speed range of the ESC test for Euro III led to an increase in fuel consumption of around 4% compared with Euro II. Compared with Euro III engines, it is assumed that the fuel consumption of Euro IV and Euro V engines will further decrease by 7% and 5% respectively.

Despite the tightening of the NO_x emission limits from 9 g/kWh for Euro I engines to 7 g/kWh for Euro II, Euro II engines have, on average, 5% higher NO_x emissions than Euro I. The NO_x emission levels of the Euro III vehicles (emission limit 5 g/kWh) are below those of Euro II, but the magnitude depends upon the driving cycle. Over motorway cycles Euro III NO_x emissions are around 20% lower than those of Euro II, but at low speeds the NO_x emissions of Euro II and Euro III engines are roughly equal. This results from the different engine loads over the cycles. During low-speed driving there is a high proportion of low engine speed operation, whereas the type approval cycle relevant to Euro III engines (ESC) contains no test points. Over these ranges the engines are optimised for low fuel consumption, resulting in relatively high NO_x levels. Based on the assumptions described above, the NO_x emissions of Euro IV vehicles are predicted to be approximately 40% lower than Euro III engines, and for Euro V vehicles the NO_x reductions are assumed to be 60% lower than for Euro III. But because of the complexity of these future engine concepts, the prognosis has to be regarded as uncertain.

Figure B5-11 shows the results for PM for the same HDV category. PM emissions dropped by nearly 60% from pre-Euro I to Euro II vehicles. The reduction was even greater for smaller HDVs, since the larger engines introduced cleaner technologies within the pre-Euro I category. The modelled PM emission levels were roughly the same for Euro II and Euro III vehicles, but varied with the cycle under consideration. Again, the emissions over low-speed cycles were relatively high for Euro III, whereas over the motorway cycles the PM levels of Euro III were clearly lower than Euro II. For Euro IV and Euro V vehicles a reduction of more than 80% is predicted compared with Euro III.

For HC emissions – shown in **Figure B5-12** - clear reductions were found from Euro I to Euro II. Because of the oxidation catalyst in the exhaust gas after-treatment system from Euro IV onwards, HC emissions are predicted to be almost negligible. Similar results were found for CO, but both CO and HC are not critical exhaust gas components for HDVs.

The emission results from PHEM were compared with the emission factors in HBEFA1.2[24]. These emission factors have also been implemented in the COPERT III emission model, and are commonly used in Europe. Unfortunately, the vehicle data used in HBEFA1.2 were not defined in any document. Additionally, the results presented above show that the relative ratio of the emission factors between the different Euro categories depends very much on the loading, the cycle and the road gradient. The results from HBEFA 1.2 suggest that constant scaling factors have been used between the Euro categories. Therefore, a comparison of the results for ARTEMIS and HBEFA1.2 is only indicative.

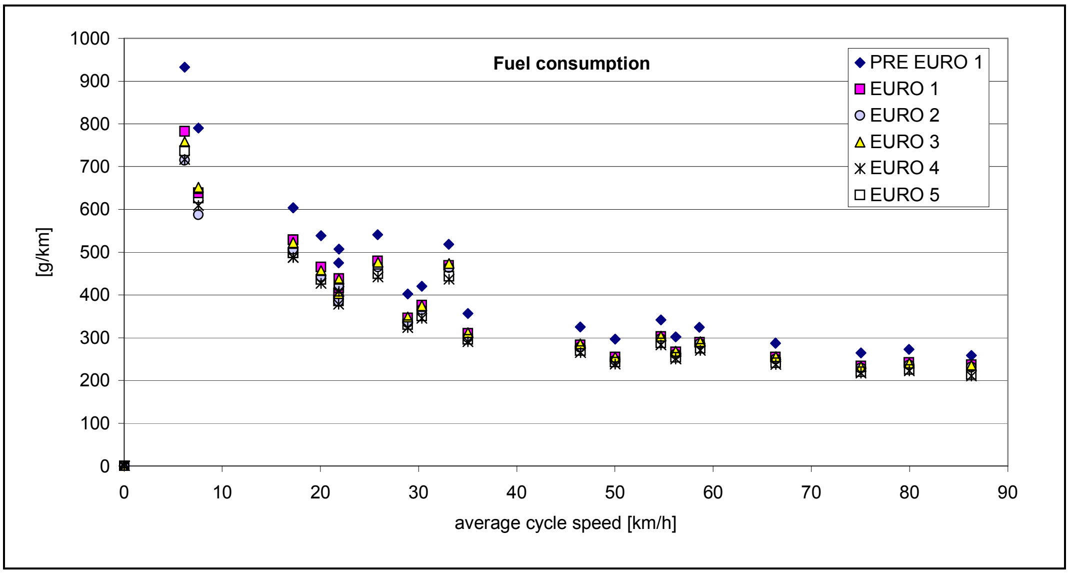


Figure B5-9: Simulated fuel consumption for truck trailers and articulated Trucks 34 to 40 tonnes, 50% load, 0% road gradient.

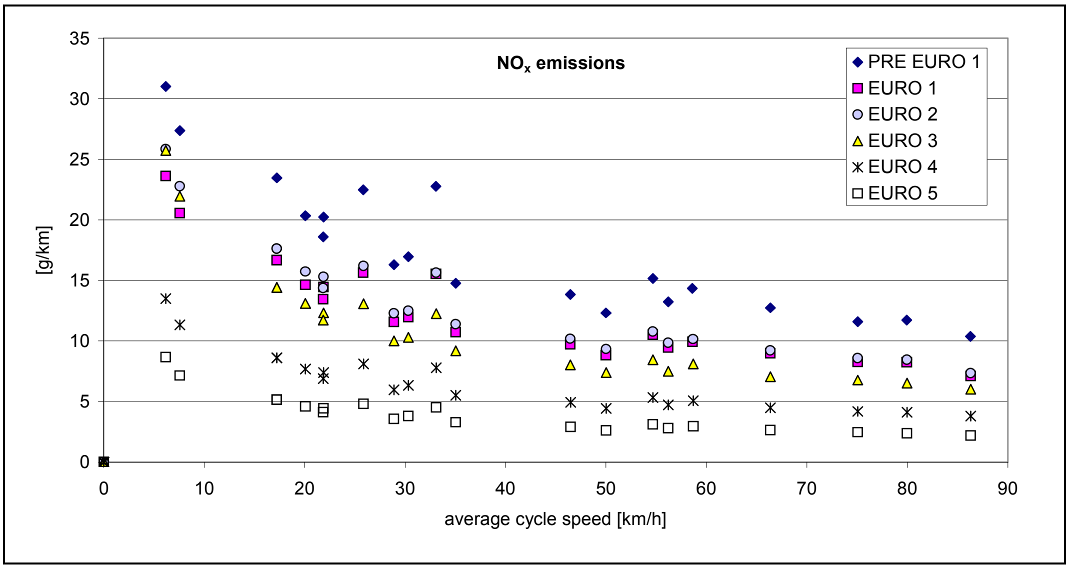


Figure B5-10: Simulated NO_x emission factors for truck trailers and articulated Trucks 34 to 40 tonnes, 50% load, 0% road gradient.

[24] The latest version of HBEFA is version 2.1, which was published in February 2004. The calculation of HDV emission factors in HBEFA2.1 was also based on PHEM. Differences to the emission factors calculated for ARTEMIS in February 2005 resulted from the inclusion of more available measurements, further model development and a new set of representative driving cycles.

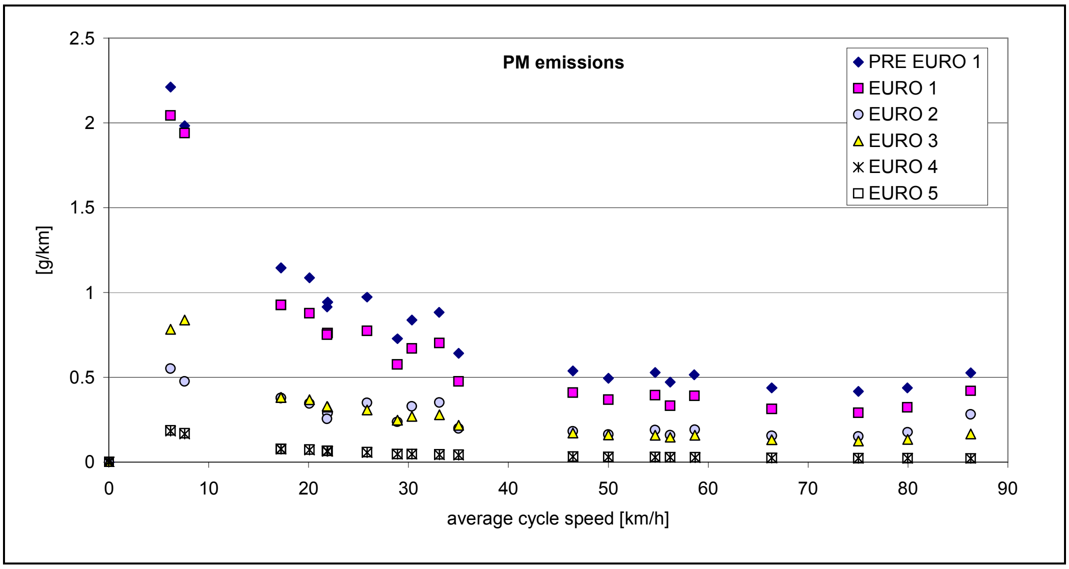


Figure B5-11: Simulated PM emission factors for truck trailers and articulated trucks 34 to 40 tonnes, 50% loaded, 0% road gradient.

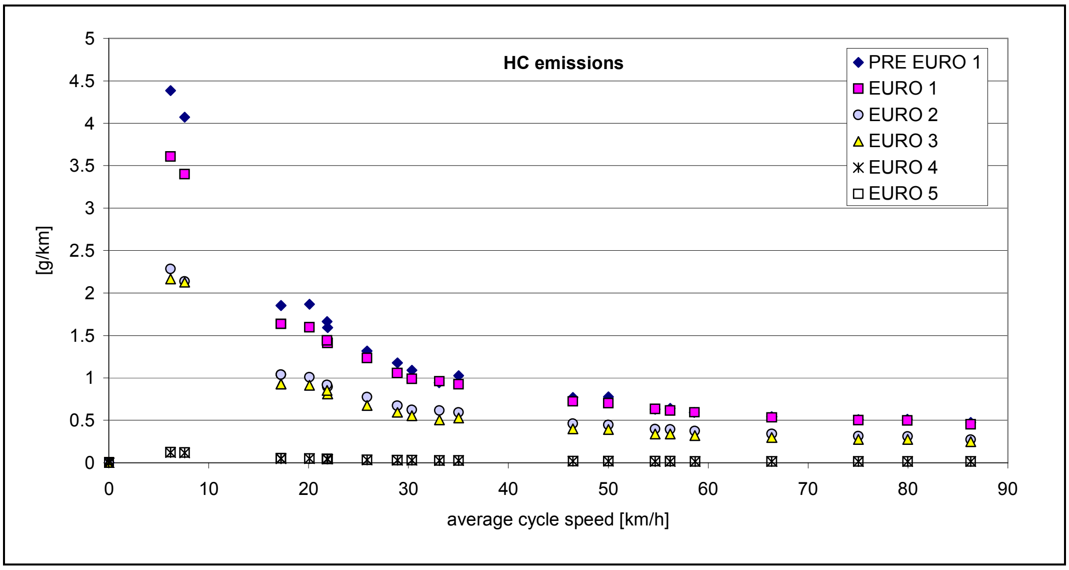


Figure B5-12: Simulated HC emission factors for truck trailers and articulated Trucks 34 to 40 tonnes, 50% loaded, 0% road gradient.

To provide a rough comparison, the HDV category 'truck trailer and articulated truck 34 to 40 tonnes' was used. In the new model this category has 39.8 tonnes maximum allowed gross weight, with an empty vehicle weight of 15.1 tonnes. A loading of 50% corresponds to 12.35 tonnes. The simulations in the HBEFA2.1 may have been conducted for any maximum allowed weight between 34 and 40 tonnes, and the definition of 'half loaded' is unclear, since the empty vehicle weight is not known. However, for the aforementioned HDV category the simulated fuel consumption for pre-Euro I vehicles agreed reasonably well, so it is assumed that the vehicle characteristics in the old and new models were reasonably similar. The fuel consumption values simulated for three main traffic situations (motorway, rural, urban) in ARTEMIS were slightly lower than those in HBEFA 1.2, especially for motorway driving. The NO_x emission factors simulated for pre-Euro I and Euro I were similar in ARTEMIS and HBEFA1.2. As expected, the updated NO_x emission factors simulated by PHEM for Euro II and Euro III were much higher than those in HBEFA 1.2. Since the engine emission data for pre-Euro I were mainly from the same source as PHEM, the resulting agreement was expected. Euro II and Euro III engines were not measured for HBEFA 1.2 but were determined by considering the reduction in the emission limits at type approval. In contrast, PHEM uses measured engine maps for these categories. The new PM emission factors for pre-Euro I and Euro I were lower for urban and rural and higher for motorway driving compared with HBEFA1.2. For Euro II vehicles and motorway driving PHEM predicts much higher emission levels than HBEFA12, but similar emission levels for rural and urban driving. The PM emissions for Euro III were, in general, higher in the ARTEMIS emission model.

For CO the emission factors were rather similar for the pre-Euro I category. For newer HDVs PHEM gave much higher CO emissions. It is likely that the emission factors from HBEFA 1.2 were reduced according to the type approval values for Euro I to Euro III. In reality, the CO emission levels of HDVs have already been far below the limit values for Euro I so there was no need to reduce CO systematically for Euro II and Euro III engines. Thus, CO was reduced only as a side effect of measures to reduce PM emissions and other improvements in the combustion technology. However, the emission levels for CO are still in line with the limits, and are not critical from the environmental point of view.

B5.8 Conclusions and recommendations

The following conclusions and recommendations were drawn from the ARTEMIS work on heavy-duty vehicles:

B5.8.1 Conclusions

(i) The ARTEMIS work has provided new insights into the emission behaviour of modern HDVs. The measurement programme and the method developed for the simulation of HDV emission factors proved to be capable of handling new engine technologies, as well as the various demand of model users.

(ii) The collection of existing data and the measurement programme clearly benefited from co-operation with COST 346, HBEFA and national activities. Without this co-operation the number of available measurements would have been much smaller.

(iii) PHEM, which was developed for the simulation of HDV emission factors, provides accurate predictions of emissions from HDVs in any traffic situation.

(iv) For interpolation of CO, HC, NO_x and PM emissions and fuel consumption a standardised emission map format was developed. This allowed the incorporation in the model of emission maps from a varied range of engines of different sizes and from different sources, and increased the sample size per engine category by a factor of ten, rendering the emission factors much more reliable.

(v) The main model asset for achieving high accuracy is the transient correction function, which transforms the emission levels from the steady-state engine map to levels which can be expected for transient engine loads.

(vi) The highest accuracy in the prediction of HDV emissions can be achieved using driving cycles which are measured exactly for the traffic situation under consideration. Using the ARTEMIS emission factor database avoids the effort of measuring driving behaviour, but can increase the error since it is not possible to cover all potential real-world traffic situations with pre-defined driving cycles.

(vii) Due to the large and non-linear effects on emissions of vehicle size and vehicle load, as well as the effects of the driving cycle and the road gradient, the use of simple correction factors for these model parameters, in combination with speed-dependent regression functions for the basic emission factors, is not recommended where high accuracy is required.

(viii) Existing formulae can be used to predict, with reasonable accuracy, the changes in emissions due to different fuel properties, although the effects are actually rather small.

(ix) HDVs exhibit stable emission behaviour during their lifetimes. However, this may change with the introduction of more sophisticated emission-control technologies in the near future.

(x) Since the introduction of the Euro I standard, NO_x emission levels for real-world driving conditions have not decreased as much as might have been predicted from the type approval limits. The main reason for this is the more sophisticated technologies being used for engine control and fuel injection, which allow different specific optimisation over different regions of the engine map.

(xi) Fuel efficiency clearly has a much higher market value than low real-world emissions. Since the market situation encourages manufacturers to optimise fuel consumption wherever possible, the old ECE-R49 type approval test was not able to guarantee low NO_x emissions for the new generation of electronically controlled engines (post 1996). This situation improved with the introduction of the ESC test for Euro II.

(xii) Since engine technology has progressed quite rapidly since 1996, and a further technological leap will be required for Euro IV and Euro V, it cannot be sure that the combination of the ESC and ETC cycles in the current type approval test will prevent real-world emission levels being significantly higher than at type approval.

(xiii) The emission behaviour of Euro IV and Euro V vehicles is very hard to predict at the moment since the technologies used are new and no production vehicles were available for measurement in ARTEMIS. It is expected that in-use tests will be necessary to prevent emission levels during real-world driving exceeding the type approval values.

B5.8.2 Recommendations

The type approval limits and test procedure have to be well-balanced to produce cost-effective benefits for air quality. Only lowering the limit values clearly gives an incentive to introduce off-cycle optimisation.

A dedicated type approval test for existing technologies may soon have shortcomings for future technologies. Thus, in-use tests on the complete vehicle, based on random real-world driving and using on-board emission measurement equipment or roller test bed measurements, may be an important tool in the future if low emissions are to be guaranteed. Such in-use tests could also be used to check the durability of the new technologies introduced with Euro IV and Euro V. Such tests would have to be performed in time to enable action to be taken within the production lifetime of the vehicles. This does mean, however, that such a programme would have to commence immediately.

An update of the emission factors is recommended as soon as Euro IV and Euro V vehicles enter the market. Regular updates of the emission factors for actual HDV technologies will be highly important, especially for monitoring compliance with existing European emission and air quality targets for NO_x and PM_{10}. In-use tests could also be used to feed the PHEM emission factor model with data, as long as the test programme is designed accordingly. Such an approach could lower the cost of updates significantly, since measurements on the engine test bed for in-use Euro V HDVs may become very expensive due to the complex technology. Moreover, engine tests without special engine control units may be impossible for future heavy-duty engines, and thus new methods are necessary if tests which are independent from the manufacturers are to be performed.

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B6 TWO-WHEEL VEHICLES

B6.1 Introduction

B6.1.1 Overview

This Section of Part B describes the findings of the ARTEMIS work on emissions from powered two-wheel vehicles (hereafter referred to as 'two-wheel vehicles'). It summarises the work of Elst *et al.* (2006).

Due to the regular introduction of new exhaust emission legislation and the tightening of the limits for CO, HC, NO_x and PM, the emission levels of passenger cars and HDVs have reduced significantly. There have been fewer changes in the legislation relating to two-wheel vehicles. The Stage 1 ('Euro I') of Directive 97/24/EC, which became effective in 1999, introduced more stringent limits than the existing ECE R40 Regulation. In 2003, Stage 2 (Euro II) of 97/24/EC entered into force. This reduced the limits further, but without changing the type approval test cycle. In 2006 (Euro III) the emission limits were reduced further still, and the type approval test cycle was changed. The ECE-R40 cycle (four urban cycles) was replaced by a combination of the UDC and EUDC cycles used for passenger cars. Manufacturers and certified agencies were also allowed to use the world harmonised type approval test cycle (WMTC) for type approval.

When the ARTEMIS project began, only a few emission models were available for two-wheel vehicles. Models generally used the methodology described in HBEFA (UBA, 1999), which was based upon emission tests on 24 motorcycles, mainly measured in Switzerland, and all before 1996. More recent emission results were available, but these tended to be based on the type approval cycle and relatively new motorcycles. The representativeness of these test results was therefore in doubt. Because of the diversity of motorcycles and their potential for high speeds and high accelerations, real-world driving was considered to be significantly different from the speed-time pattern of the UDC. Additional measurements on in-use vehicles over real-world test cycles were therefore required.

B6.1.2 Objectives and summary of programme

One of the main objectives of ARTEMIS was to develop a set of representative emission factors for in-use two-wheel vehicles. An extensive measurement programme was conducted, involving tests on 90 motorcycles. The work focused on motorcycles with an engine capacity greater than 50 cm^3. Mopeds with an engine capacity of less than 50 cm^3 were not considered. The programme included:

(i) A representative selection of two-wheel vehicles in-use in Europe.

(ii) A selection of representative real-world test cycles, together with a representative gear-shift model.

(iii) A road-load simulation procedure which corresponded to real-world conditions.

Before the measurement programme began, a 'round-robin' test programme was carried out to check whether the emission results over different test cycles were reproducible when measured in different laboratories, and to identify potential measurement difficulties. Four laboratories - Fachhochschule Biel (FHB), KTI, TNO-Automotive and TÜV-Nord - participated in the round-robin programme. The effects on emissions of cold starts, fuel properties and inspection and maintenance were also examined.

Links were established with several groups and programmes outside the ARTEMIS project, notably the PARTICULATES project, separate national research programmes, the ISO standardisation group responsible for revising the standards for testing two-wheel vehicles (ISO TC22/SC22/WG17), and the CITA 2nd research programme on roadworthiness testing.

B6.2 Round-robin test programme

B6.2.1 Background

An extensive report by Elst *et al.* (2001) described the round-robin test programme. It should be noted that the round robin was completed in 2001, and therefore some of the conclusions and recommendations may no longer be of relevance. Where reference is made to Directive 97/24/EC, the status of that Directive in 2001 is implied.

The objectives of the round-robin programme were fourfold:

(i) To check whether measurements conducted on the same motorcycle, over different test cycles, and in the different participating laboratories, were reproducible.

(ii) To identify and solve particular measurement problems before the main measurement programme began.

(iii) To check the sensitivity of emissions to changes in different parameters.

(iv) To check whether data measured earlier by FHB (Czerwinski *et al.*, 1997, 1998) could be added to the ARTEMIS emission factor database.

B6.2.2 Method

The round-robin measurement programme was carried out over a period of 14 months. Two different motorcycles were used: a two-stroke scooter with no exhaust gas after-treatment and a four-stroke 'sports bike' with a three-way catalyst. The round robin began at TNO in Delft. The motorcycles then travelled to KTI (Bucharest), FHB (Biel), TÜV-Nord (Hannover) and back to TNO. The petrol fuel used in the programme was similar at all laboratories. Because KTI were requested to repeat the test series, the round robin was completed in Hungary.

B6.2.3 Results, conclusions and recommendations

The tests showed that, in general, chassis dynamometer emission measurements carried out on motorcycles in different laboratories agreed, depending on the pollutant, within a range of about ± 25%. This result was regarded as satisfactory and a solid basis for starting the main measurement programme. Some of the results from the first tests carried out at KTI were different to the results obtained in the three other laboratories. After the programme had finished, KTI upgraded its laboratory. Additional emission and fuel consumption measurements were then carried out, and these indicated that the improvements made brought the results in line with those from the other laboratories. The results also indicated that the data measured by FHB in the past could be incorporated in the ARTEMIS database.

General conclusions and recommendations

The following general conclusions and recommendations were drawn from the round-robin tests:

- The range of emission levels for two-wheel vehicles can be much wider than that for passenger cars (*e.g.* 0.3-30 g/km for CO).
- Brake load settings can be relatively small and therefore difficult to simulate.
- Highly dynamic test cycles, in combination with a high power:mass ratios and/or the presence of electronic engine management systems or exhaust gas after-treatment, may result in poor repeatability of emission measurements.
- Improvements to the running resistance table prescribed by Directive 97/24/EC[25] should be made, since the brake load settings are not suitable for high-speed cycles.
- Test drivers should be acquainted with the cycles to be driven and the specific behaviour of the test vehicles.
- Improvements to the response times in brake load simulations are required, as test cycles will become more dynamic.
- There should be further investigation of the poor repeatability of emission measurements for modern vehicles equipped with three-way catalysts.

Conclusions and recommendations for the ARTEMIS measurement programme

The recommendations for the measurement programme of ARTEMIS included the following:

- Tests on vehicles with comparable emission levels should be conducted during the same session using appropriate analyser ranges and tunnel air flow rates.
- Each laboratory should select an optimal sample flow based on the motorcycle to be tested, the test cycle and the available analyser ranges.
- A single, easy-to-use method should be defined for brake load settings and analyser calibration procedures.
- Directive 97/24/EC prescribes that the dilution air should be analysed using the same analyser range as that used for the diluted exhaust gas. Since the selected range for analysing the exhaust gas could be very high, zero values might be obtained for the dilution air. The dilution air should be analysed over a more suitable (lower) range, and the analyser should be calibrated over both the selected ranges before the bags are analysed.
- Test drivers should be acquainted with real-world cycles and the behaviour of the vehicles to be tested.

This work may have constituted the first round-robin test for motorcycles. The exercise was critical for the success of the subsequent tasks within ARTEMIS. Additionally, the work assisted in the formulation of a technical annex for an exhaust gas measurement Directive.

B6.3 Definition of the measurement programme

B6.3.1 Motorcycle categorisation

The two-wheel vehicles tested within ARTEMIS reflected the actual composition of the European fleet. The categorisation of two-wheel vehicles for testing purposes was based upon a review of the critical parameters affecting emission behaviour. This was conducted from a theoretical point of view; available emission data were used, but for most categories only limited

[25] Directive 2003/77/EC contains a new running resistance table.

measurements were available. After the most important parameters had been identified, the actual composition of the European motorcycle fleet was determined using available statistics. Because of the wide variation in vehicle weight, engine capacity, engine type (two- or four-stroke) and exhaust gas after-treatment technology, it is very important to define appropriate vehicle categories. The main parameters considered are listed below (Rijkeboer, 2000).

Engine capacity: Since 'mopeds' (< 50 cm^3) were not taken into account within ARTEMIS, the following distinction was made: 50-125 cm^3, 126-250 cm^3, 251-500 cm^3, 501-750 cm^3, 750-1000 cm^3 and > 1000 cm^3.

Engine type: Throughout Europe two-wheel vehicles are equipped with two-stroke and four-stroke petrol engines (except for one diesel model and a few electric models). For the purpose of categorising motorcycles a distinction between these two main engine types was therefore required. Because two-stroke engines tend to have a small engine capacity, and are mostly used on scooters, the distinction was only applied to motorcycles with an engine capacity of less than 250 cm^3.

Exhaust gas after-treatment: In time, more two-wheel vehicles will be equipped with exhaust gas after-treatment systems (*e.g.* oxidation catalyst, 'coated tube' or three-way catalyst), but relatively few data were available to evaluate their performance under real-world driving conditions. For categorisation purposes, a distinction between catalyst and non-catalyst motorcycles was therefore applied.

Age and mileage: The age of a vehicle is linked to its technology level and the emission legislation to which it conforms. Three age categories were defined: (i) 0-3 years old, (ii) 3-10 years old, and (iii) > 10 years old. The age categorisation was valid for the year 2002, the year in which the main measurement programme was conducted. This meant that the age category '0-3 years' included all Euro I vehicles.

Legislative category: At the time when the categorisation of two-wheel vehicles was developed, three different legislative categories were valid for Europe. These were ECE R40-00, ECE R40-01, and 97/24/EC Stage 1 (Euro I). As the legislation category is directly related to the age of the vehicle, no distinction in terms of legislative category was applied to the categorisation of vehicles for the measurement programme.

Model

Different types of motorcycle models are currently available on the market. Since each type of motorcycle has its own characteristics, a broad division between the following model classes was established: 'scooters', 'off-road', 'enduro', 'touring', 'choppers', 'sports' and 'super-sports'.

The next step was to determine the composition of the European vehicle fleet according to the parameters mentioned above. However, few fleet statistics for two-wheel vehicles were available for either Europe or single European countries. The most recent registration statistics were combined to estimate actual fleet proportions. This approach might lead to discrepancies with the actual fleet on the European road since the recent registrations are not always representative of new registrations in other years, and trends in buying behaviour with respect to engine capacity, engine type, size and model of a vehicle could change over the years.

Table B6-1 gives the actual number of vehicles tested by engine capacity, engine type and catalyst category. The distributions by age class and model type are shown in **Tables B6-2** and **B6-3**. The initial number of 90 motorcycles to be tested for ARTEMIS was increased to 115 through co-operation with the CITA programme.

B6.3.2 Test cycle selection

The test cycles used in the measurement programme had to contain all the information needed to obtain reliable and representative real-world emission factors. To select appropriate test cycles meeting this requirement, an inventory of available test cycles for two-wheel vehicles was conduced. The test cycles assessed were (in alphabetical order):

(i) CADC[26] (Common ARTEMIS Driving Cycle) (André *et al.*, 2000).
(ii) FHB real-world test cycles for motorcycles. The FHB test cycle contains four parts: 'Zentrum' (town centre), 'Peripherie' (ring road), 'Überland' (rural) and 'Autobahn' (motorway).
(iii) HYZEM real-world test cycle for passenger cars, developed by INRETS (update of MODEM).
(iv) IDC (type approval test cycle for India).
(v) MODEM real-world test cycle for passenger cars, developed by INRETS.
(vi) RWTÜV/UBA proposal[27] (UDC and adapted EUDC with enhanced accelerations).
(vii) UDC (current European type approval test procedure) + EUDC.
(viii) US-FTP (American type approval test cycle).
(ix) WMTC.

Most of these test cycles were derived for passenger cars. Only the FHB real-world test cycles, RWTÜV/UBA and WMTC took into account, or had a direct link with, motorcycle driving. However, at the time of the ARTEMIS measurement programme the WMTC test cycle had not have reached its final status, and was therefore not used. In order to determine

[26] The CADC driving cycle consists of urban, rural and motorway parts. Each of these parts is divided in sub-cycles which were representative of certain 'traffic conditions'
[27] Complete passenger car test cycle with enhanced acceleration. Original synthetic cycle adapted to high kW/tonne ratio of motorcycles. Compromise between certification cycles and two-wheel vehicle characteristics.

whether the test cycles were representative of real-world motorcycle driving, a number of specific characteristics were evaluated (*e.g.* speed, relative positive acceleration).

TableB6-1: Numbers of vehicles tested.

Engine capacity (cm^3)	Engine type	Catalyst	Total tested
51-125	2-stroke		12
		✓	1
	4-stroke		17
		✓	2
	All		32
126-250	2-stroke		5
	4-stroke		13
		✓	1
	All		19
251-500	4-stroke		11
501-750	4-stroke		21
		✓	3
	All		24
751-1000	4-stroke		13
		✓	2
	All		15
> 1000	4-stroke		9
		✓	5
	All		14
Total			115

Table B6-2: Division of the test vehicles by age.

Engine capacity (cm^3)	Engine type	Catalyst	Age (years)		
			0-3	3-10	>10
51-125	2-stroke		5	7	
		✓	1		
	4-stroke		6	11	
		✓	2		
126-250	2-stroke		2	3	
	4-stroke		5	8	
		✓	1		
251-500	4-stroke		4	4	3
501-750	4-stroke		9	8	4
		✓	3		
751-1000	4-stroke		6	5	2
		✓	2		
> 1000	4-stroke		3	3	3
		✓	2	3	
Total			51	52	12

Table B6-3: Division of the test vehicles by model class

Engine capacity (cm^3)	Engine type	Model class					
		Catalyst	Chopper	Off road	Scooter	Sports	Touring
51-125	2-stroke				10	2	
		✓			1		
	4-stroke			2	15		
		✓			2		
126-250	2-stroke				5		
	4-stroke				12		1
		✓			1		
251-500	4-stroke			2	2		7
501-750	4-stroke			2	1	3	15
		✓		2		1	
751-1000	4-stroke		1	3		6	3
		✓					2
> 1000	4-stroke					1	8
		✓				2	3

Since type approval according ECE R40 and 97/24/EC requires pre-conditioning over two of the four elementary cycles of the UDC, it was decided to include pre-conditioning in the measurement programme. The emission results obtained over the pre-conditioning cycle were used to derive cold-start emissions.

Gear-shifts were available for the type approval cycle, but not for the FHB cycles and the CADC (gear shifts for passenger cars). A similar gear-shift model to that in the WMTC was used ARTEMIS. More details can be found in the ARTEMIS measurement protocol that was developed to assist the laboratories during the measurements (Elst, 2002).

B6.3.3 Pollutants

The measurements were conducted at the TNO-Automotive, TÜV-Nord and KTI laboratories. The pollutants measured were CO, THC, NO_x and CO_2. Emissions were measured according to the procedures laid down in Directive 97/24/EC. Emissions were expressed in grammes per test, grammes per hour or grammes per kilometre. Fuel consumption was calculated using the carbon balance method, as described in Directive 93/116/EC. However, the methodology proposed in the Directive uses a fixed value for fuel density. Work conducted in ISO/TC22/SC22/WG17 showed that the density of the fuel used has an influence on the final result. It was therefore decided to include this parameter, as laboratories in different countries use different fuels. Particulate matter (PM) was not included in the ARTEMIS programme for two-wheel vehicles as the measurement procedure was still under investigation.

The main aim of the ARTEMIS work was to generate a large database of emission factors for different types of motorcycle over various test cycles. As the high cost of on-line emission measurements would have resulted in tests being conducted on significantly fewer vehicles, a decision was made to focus on quantity, and to measure emissions mainly in bags. TÜV-Nord, however, collected both bag samples and on-line measurements during all tests. The resulting data provided insights into the emission behaviour of motorcycles under particular conditions, and turned out to be a critical factor in the development of the emission model.

B6.3.4 Chassis dynamometer settings

At the start of ARTEMIS the following Directives were available:

International - UN-ECE (ECE R40)
Europe - (Directive 97/24/EC, US (US-FTP Part 86, subparts E and F)
Japan - (Road Vehicle Act, Article 41, *Systems and Devices of Motor Vehicles*).

However, with regard to the development of the WMTC, ISO/TC22/SC22/WG17 was requested to revise ISO standard 11486:1993 (*Two-wheel motorcycles - Fuel consumption measurements - Chassis dynamometer setting by coast-down method*), which contains the procedure for setting the chassis dynamometer to simulate road loads. The work of ISO WG17 was in progress at the time the measurement programme of ARTEMIS started, and therefore an existing method was used.

All the available Directives described procedures for determining chassis dynamometer setting via on-road measurement or the application of an alternative table method. The first procedure provides a description how the measurements should be conducted, the equipment to be used, and the data processing required in order to determine settings which are representative of a specific motorcycle. The table method is based upon measurements carried out in the past. A second-order polynomial describes road load as a function of vehicle speed for different mass classes. The selection of the most accurate of the available options was carried out by RWTÜV (Steven, 2001). The study showed that for the alternative table method the US-FTP should be used. Minor differences existed between the procedures involving on-road measurements. However, it was decided that single Directive (again, US-FTP) should be used to determine chassis dynamometer settings. For both procedures the actual vehicle mass (including the driver) is needed to determine inertia. However, the Directives also contained different definitions (*e.g.* for weight of the driver). In this case the European legislation was used, since this was the most detailed.

B6.3.5 Other relevant issues for the measurement programme

During the round-robin tests, differences were apparent between the way in which tests were conducted at the different laboratories (Elst *et al.*, 2001). These were addressed as follows:

Dilution ratio: Depending on the motorcycle to be tested, the test cycle to be driven, and the analyser ranges, a suitable dilution ratio should be chosen in order to measure all pollutants with sufficient accuracy.

Procedure for analysing bag samples: The procedure to be used to analyse the bags (for dilution air as well as for exhaust gas) was improved following the recommendations of the round-robin programme. A flow chart describing the procedure for emission bag analysis was developed to ensure common understanding.

Vehicle condition: Each motorcycle had to have been driven for at least 1,000 km before the test, but otherwise vehicles were tested in the 'as received' condition.

Deceleration phases: In the type approval test, specific operation is required during deceleration phases. However, this specific operation might not be valid for real-world operation, and therefore was not be applied during such cycles.

Engine starting, restarting and emission sampling: The procedure used was a combination of both the European and US Directives. The pre-conditioning cycle conducted before the type approval cycle included an engine start. All other test cycles were started with a running engine. Again, a detailed procedure was developed.

Choke operation: Since most of the motorcycles tested were still equipped with a manual choke, a specific procedure was included for choke operation.

Data processing: A test report template was developed to ensure consistency.

These (and other) items are included in the ARTEMIS measurement programme instructions provided by Elst (2002).

B6.3.6 Other topics

The standard measurement programme mainly focused on obtaining a large number of hot exhaust emission results for various motorcycles. In addition, ARTEMIS also addressed cold-start emissions, the effects of fuel properties, and the effects of inspection and maintenance.

Cold-start emissions

Most motorcycles on the road still use a carburettor for air/fuel mixture preparation, do not have a catalyst, and have a manual choke for cold-start fuel enrichment. However, increasing numbers of new motorcycles are equipped with fuel injection and electronic mixture control, often in combination with a catalyst. In addition, the share of new mopeds (and some motorcycles) equipped with an automatic choke is increasing. Concerning after-treatment, common alternatives to the three-way catalyst are oxidation catalysts, coated-tubes and secondary air injection systems, the latter also being applicable in combination with one of the catalyst systems.

Several studies carried out in the past by FHB (Czerwinski *et al.*, 2000, 2001, 2002) and EMPA (Weilenmann *et al*., 2002) have dealt with the topic of cold-start emissions from two-wheel vehicles. In these studies measurements were conducted using various urban test cycles with cold and hot engines, but only a few vehicles were tested. it was concluded that the results of these studies were insufficient for modelling purposes, and additional measurements were required in ARTEMIS.

The type approval test cycle prescribed in ECE R40 and Directive 97/24/EC is conducted with a hot engine, and therefore includes a preconditioning phase based on two urban test cycles. By adding the type approval test cycle to the ARTEMIS measurement programme it was possible to measure emissions during the preconditioning cycle, and therefore to obtain cold-start emission data. The results from the round-robin tests showed that the engines of both motorcycles reached their operational temperature during the pre-conditioning phase (Elst *et al.*, 2001).

In addition to the tests conducted in the main measurement programme of ARTEMIS, a study was carried out by EMPA (Vasic *et al*., 2004). The study included cold-start emission measurements in summer (engine start temperature of 23 ^{o}C) and winter (5 ^{o}C) over the WMTC or real-world test cycles. The results for eight motorcycles were available for the project. The validation process of the WMTC (Steven, 2004), and the development of equivalent emission limits for the WMTC for Euro III (Bonnel *et al.*, 2005), provided further information.

Effects of fuel properties

Additional measurements were carried out by KTI to address the effects on emissions of fuel properties. Five motorcycles were tested. The vehicles had a wide range of engine capacity and physical dimensions, but none of them was equipped with an exhaust gas after-treatment system. The motorcycles were tested over seven driving cycles, and using two different fuels - one fuel which met current requirements and another which complied with near-future requirements. As the measurements were conducted at KTI , Hungarian market fuel was selected as the current fuel. The selected future fuel met the requirements laid down for Category 4 in the World Wide Fuel Charter (WWFC[28]) (WWFC, 2002). The principal differences between these fuels were sulphur content (23 ppm for Hungarian market and 3.4 ppm for WWFC4 fuel), olefins (11.2 against 0.4 vol%), aromatics (31.9 versus 26.5 vol%) and oxygen content (0.58 against 1.74 vol%).

Effects of inspection and maintenance

The effects of inspection and maintenance on exhaust emissions from 25 motorcycles were investigated in a project financed by CITA. The main objective of this was to establish a roadworthiness testing procedure for motorcycles with regards to exhaust emissions and noise. In both the CITA project and ARTEMIS the type approval test cycle and the FHB cycles were included (Elst, 2002). Furthermore, 15 motorcycles were tested at the AVL-MTC laboratory in Sweden for the CITA project, and these results were also available for ARTEMIS. However, the measurement programmes differed in terms of the maintenance status of the vehicles. In the CITA project a vehicle was subjected to maintenance when its emissions exceeded the relevant limits. The motorcycles tested within ARTEMIS were tested as they were received, without any additional maintenance. The results of the CITA project are summarised by Elst *et al*. (2002).

B6.4 Results of the measurement programme

B6.4.1 Hot emissions

In the ARTEMIS measurement programme, 115 two-wheel vehicles were tested using the protocol defined by Elst (2002). The results obtained are summarised below.

[28] The World Wide Fuel Charter is a joint effort by European, American and Japanese automobile manufacturers and other related associations, and recommends global standards for fuel quality, taking into account the status of emission technologies. Category 4 fuels will be applied in future vehicles which will meet very stringent emission limits.

Driving cycle effects

For CO:

- Emissions were similar over the type approval and real-world test cycles when the emission levels were above 20 g/km.
- For some cases below 20 g/km CO, emissions over the real-world cycles were generally are higher than those over the type approval cycle.
- For Euro II motorcycles the CO emissions over the real-world test cycles were much higher than emissions over the type approval cycle.

For HC:

- When HC emissions were higher than 6 g/km (*i.e.* older motorcycles), the emission levels over type approval cycles and real-world cycles were similar.
- Most of the test vehicles had higher HC emissions over real-world test cycles.

For NO_x:

- In general, NO_x emissions were higher over real-world test cycles, probably as a result of the higher accelerations and engine load.

For CO_2:

- Compared with the type approval test cycle, CO_2 emissions were lower over the FHB 'Zentrum' real-world cycle, even though the latter was more dynamic and had a higher average speed. However, the FHB Zentrum cycle contained fewer and shorter stops, and accelerations from zero speed influenced the CO_2 emissions.
- CO_2 emissions over the CADC urban test cycle were, in general, slightly higher than emissions over the type approval test cycle.

It appeared that some of the tested motorcycles might have been calibrated for the type approval cycle. Another general conclusion was that the differences in emissions between the real-world test cycles (FHB Zentrum and CADC urban) was not very large for CO, HC and NO_x. The emission results over the urban test cycles (CADC Urban, FHB Zentrum and Peripherie) and rural test cycles (CADC rural and FHB Überland) were also assessed. The main conclusions were:

For urban cycles:

- On average, CO, HC, NO_x and CO_2 emissions were lower over the FHB cycles compared with the CADC urban cycle.
- The FHB Zentrum results were slightly lower than the CADC urban results. However, the average speed and RPA did not differ greatly, which indicates that other parameters might be related more closely to emissions (*e.g.* percentage of stops).
- The higher average speed but less dynamic FHB Peripherie test cycle emission results were the lowest for all pollutants, probably as a result of the lower number of rapid accelerations.

For rural cycles:

- The CO, NO_x and CO_2 emissions over the FHB Überland cycle were lower than those measured over the CADC rural cycle. However, HC emissions were slightly higher.
- Compared with the urban test cycle results, the results over the rural test cycles were more variable.

The general conclusion was that emissions measured over the CADC urban and rural cycles were higher than those measured over the FHB cycles. Apart from the results for a few specific motorcycles, on average the emissions measured over the various test cycles were of a similar order of magnitude. However, for newer vehicles the differences between type approval and real-world cycles are increasing.

Laboratory effects

Due to restrictions with regard to the motorcycles that were available for testing and the requirement to select vehicles in order to meet the categorisation that was drawn up, the composition of the vehicle sample tested in the various laboratories differed. Nevertheless, general conclusions could be drawn from the average results of the laboratories:

- CO and HC emissions differed considerably between the laboratories. However, the averages calculated for the four-stroke motorcycles tested at TNO and TÜV-Nord showed similar levels for most vehicle classes.
- NO_x emissions were very low, and generally well below the Stage 1 limit of Directive 97/24/EC. The conclusions that were derived for CO and HC were also valid for NO_x.
- Average CO_2 emissions showed a similar trend when comparing the values of the different laboratories. In addition, the absolute averages of the laboratories were closer to each other than for CO, HC and NO_x.
- The levels of average fuel consumption were similar in the different laboratories for all vehicle categories. For two-stroke vehicles the high HC emissions had a significant effect on fuel consumption.

Given the variability in emissions, it was hard to draw any conclusions about laboratory comparability. Nevertheless, the results measured at the different laboratories provided an indication of average emission levels and fuel consumption for the twelve defined engine capacity/type categories. In addition, the results proved to be reliable and could therefore be used as the basic dataset to be applied for the purpose of emission model development.

B6.4.2 Cold-start emissions

The type approval test consists of six elementary urban driving cycles. The first two cycles are used for pre-conditioning, and the last four cycles are used for emission measurement. The emissions measured during the pre-conditioning cycles were used to investigate the effects of cold starting.

The 'excess' cold-start emission is given by:

$$E_{\text{cold start}}[g] = E_{\text{urban cold start}}[g] - E_{\text{urban warm running}}[g] \quad \text{(Equation B6-1)}$$

Average excess cold-start emission factors are given in **Table B6-4**. Including the results of the WMTC and EMPA studies, 280 cold-start emission values were available. However, due to the large number of vehicle categories the number of measurements for each category was quite low, and for some categories no data were available. Only the data measured in ARTEMIS were used to determine emission factors. Four-stroke engines had increased CO and HC emissions due to cold starting. The relative importance increased from pre-Euro I to Euro III, mainly due to the fact that hot emissions had decreased more than cold-start emissions. When comparing the results for Pre-Euro I to Euro III four-stroke vehicles, the absolute NO_x cold-start emission appeared to increase. If mixture enrichment during a cold start is minimised, there is a greater possibility of the mixture being lean locally, eventually causing a slight overall increase in NO_x. A decreasing cold-start enrichment is probably the result of internal engine optimisation and more accurate control of fuel injection in the newer vehicles. When CO and HC emissions increased due to a cold start, CO_2 emission decreased accordingly. This may even offset the increase in CO_2 due to higher engine friction. Ultimate CO_2 emissions were therefore used.

Table B6-4: Excess cold-start emission per category
(only vehicle categories with values are included)

Engine type	Engine capacity (cm^3)	Legislative category	CO (g)	HC (g)	NO_x (g)	FC [29] (cm^3)	CO_2 [30] (g)
2-stroke	<50	Pre-Euro I	4.52	6.86	0.03	7.49	17.94
	50-150	Pre-Euro I	5.40	6.26	0.00	11.26	27.00
		Euro I	-1.89	4.97	-0.01	-0.05	-0.13
	151-250	Pre-Euro I	7.93	6.53	-0.02	14.30	34.27
4-stroke	<50	Euro III	9.81	0.77	0.04	19.25	46.14
	50-150	Pre-Euro I	3.90	0.99	0.06	8.42	20.18
		Euro I	7.40	1.21	0.21	8.57	20.53
		Euro II	5.76	1.36	0.24	9.57	22.94
	151-250	Pre-Euro I	-1.25	0.71	0.10	9.92	23.78
		Euro I	1.77	0.62	0.09	8.18	19.60
		Euro II	2.84	0.71	0.30	10.97	26.29
	251-750	Pre-Euro I	14.21	1.35	0.03	19.97	47.87
		Euro I	39.95	2.26	0.04	29.55	70.83
		Euro II	14.06	1.68	0.03	18.17	43.55
	>750	Pre-Euro I	21.70	3.28	0.04	24.40	58.48
		Euro I	40.99	5.07	-0.01	42.85	102.71
		Euro II	17.89	2.62	0.10	20.34	48.76
		Euro III	15.51	2.00	0.19	12.66	30.35

B6.4.3 Effects of fuel properties

The results of the fuel property tests were summarised in a detailed report by Kis *et al*. (2005). The main conclusions were as follows:

- For all motorcycles CO emissions were, on average, 15% lower when using the WWFC4 fuel instead of the Hungarian market fuel. The effect was highest during the EUDC test cycle, and the trends were similar for two- and four-stroke engines.

[29] Fuel consumption was calculated by applying the carbon balance method to measured CO_2, CO and HC emissions.
[30] Measured exhaust CO_2 emission.

- For HC the WWFC4 fuel generally resulted in slightly lower emissions. Similar trends were observed for two- and four-stroke engines.
- For three of the five motorcycles tested, NO_x emissions increased by 10-20% when the WWFC4 fuel was used. NO_x emissions from the two-stroke motorcycle tested decreased by around 15%.
- Most of the motorcycles showed a significant increase (around 4%) in exhaust CO_2 emissions when they were tested using the WWFC4 fuel. No differences were observed between two- and four-stroke engines. Fuel consumption was not affected by the change of fuel.

A likely explanation for these results might be that the additional oxygen in the WWFC4 fuel reacted with CO and HC and was converted into CO_2. However, it is not clear whether only the oxygen content was responsible for this effect or if other properties also affected emissions.

B6.4.4 Effects of inspection and maintenance

The effects on emissions of inspection and maintenance were addressed in the CITA study. Within the CITA study, 105 motorcycles were tested over loaded and idle tests. Although the applicable emission limits of legislative categories ECE-R40-00, ECE-R40-01 and 97/24/EC Stage 1 were relatively high, nine motorcycles had problems complying with the Type I and Type II emission limits. For seven of these motorcycles technical inspection or maintenance could be carried out; for two motorcycles more extensive and expensive repairs were needed (*e.g.* engine revision, new carburettors). The emission data of the measurements conducted in the test cycles before and after maintenance were analysed.

Table B6-5 gives the number of vehicles that were tested before and after maintenance - also divided by legislative category - and the average, minimum and maximum improvements that were calculated for all test cycles on which measurements were conducted. Note that negative values represent increases in emissions relative to the measurements conducted before maintenance. The main conclusion was that the sample sizes were too small for the data to be employed for predictive purposes. In addition, the minimum and maximum values show significant variation, which means that the effect is also related to the test cycle that is used. Nevertheless, the data may be applied for generating average factors to be applied to estimate the effect of inspection and maintenance on the emissions for a certain vehicle fleet.

Table B6-5: Maintenance conducted and improvement on CO, HC, NO_x, ultimate CO_2 and fuel consumption (a negative value represents an increase).

Type of maintenance	No. of vehicles		Average	Minimum	Maximum
	Pre-Euro I	Euro I			
CO improvement					
Adjustment of carburettor	2	1	24%	15%	33%
Oil, air and oil filters	1	-	11%	8%	14%
Change of battery	-	2	204%	49%	358%
Oil, air and oil filters, adjustment of carburettor	1	-	-8%	-10%	-6%
HC improvement					
Adjustment of carburettor	2	1	22%	16%	26%
Oil, air and oil filters	1	-	15%	4%	26%
Change of battery	-	2	10%	-13%	33%
Oil, air and oil filters, adjustment of carburettor	1	-	-18%	-20%	-17%
NO_x improvement					
Adjustment of carburettor	2	1	44%	-28%	103%
Oil, air and oil filters	1	-	23%	-14%	59%
Change of battery	-	2	299%	101%	497%
Oil, air and oil filters, adjustment of carburettor	1	-	-1%	-4%	1%
Ultimate CO_2 and fuel consumption improvement					
Adjustment of carburettor	2	1	19%	10%	31%
Oil, air and oil filters	1	-	0%	-1%	1%
Change of battery	-	2	18%	5%	32%
Oil, air and oil filters, adjustment of carburettor	1	-	-2%	-3%	-2%

The effects of changing the battery were found to be significant for CO, NO_x, ultimate CO_2 and fuel consumption. However, the number of occurrences in reality might be very low since a broken battery - which causes much inconvenience for the driver of the motorcycle – will probably be replaced quickly. Therefore, it was decided that the effect of replacing the battery would not be included in the calculation of adjustment factors.

B6.5 ARTEMIS emission model

B6.5.1 Emission factor database

When the ARTEMIS project started several emission models (*e.g*. HBEFA and COPERT) were able to predict emissions from road transport. However, motorcycle emission modelling was mainly based on the emission results for only a few motorcycles, a limited set of test cycles, and mostly new vehicles. Models were either based on emission factors for urban, rural or motorway driving, or average-speed functions. In the ARTEMIS main measurement programme, 115 two-wheel vehicles were tested over eight different driving cycles. Motorcycles complying with the Euro I and Euro II limits were included.

The ARTEMIS measurements were entered into a database. Since the measurements were conducted on vehicles compliant with the ECE-R40 and 97/24/EC Stage 1 emission limits, data were lacking for 97/24/EC Stage 2 and 3 vehicles. However, a large number of emission measurements were available from the WMTC programme (Steven, 2004), members of the Motorcycle Industry in Europe (ACEM), the CITA 2nd study (Elst *et al.*, 2002), the EC Joint Research Centre (JRC) (Bonnel *et al.*, 2005), and the Association for Emissions Control by Catalyst (AECC, 2004).

Table B6-6 shows the numbers of vehicles in the database by legislation category. Limited data were available for current and future European legislation categories. Nevertheless, the model should also be able to predict emissions for these categories of vehicles. It was decided to determine the legislation category by obtaining the emission results of the type approval test instead of using the specified legislation. The database also contained a number of motorcycles for which the legislative category was not known.

Table B6-6: Vehicles in the ARTEMIS database by legislation category.

Legislation	Euro class	Type approval	Legislative category - updated
ECE R40-00/ECE R40-01/ECE R47	Pre-Euro I	100	183
97/24/EC Stage 1	Euro I	190	93
97/24/EC Stage 2	Euro II	22	78
97/24/EC Stage 3	Euro III	2	14
Unknown	-	66	12
Total		380	380

The vehicle categorisation was developed and applied to ensure that all two-wheel vehicle categories were included in the ARTEMIS measurement programme. The vehicles that are in the database were grouped according to the categorisation provided in **Table B6-7**.

Table B6-7: Vehicle categorisation for two-wheel vehicles in the emission model.

Vehicle category		Engine capacity	Engine type
1	Moped	< 50 cm³	2-stroke
2			4-stroke
3	Motorcycle	≤ 150 cm³	2-stroke
4			4-stroke
5	Motorcycle	150 - 250 cm³	2-stroke
6	Motorcycle		4-stroke
7	Motorcycle	250 - 750 cm³	4-stroke
8[31]	Motorcycle	> 750 cm³	

The approach to determine emission factors for motorcycles was taken from the methodology that was applied to update the two-wheel vehicles part of HBEFA (Steven, 2003). The methodology involved the following steps:

31 Since the CO_2 emissions from a motorcycle with an engine capacity of 750 cm^3 is higher than that from smaller motorcycle, a distinction with regards to engine capacity was defined for the purpose of vehicle categorisation. However, the emission levels for CO, HC and NO_x are similar for these categories.

- For each two-wheel vehicle, the on-line emission and vehicle speed data were analysed. The data were divided into 3-minute intervals for which modal emissions (in g/h) and test cycle parameters were calculated. Engine idling was treated separately.
- The results were plotted against average vehicle speed, giving a function for each two-wheel vehicle.
- The vehicles were grouped into categories.
- The functions for each group of two-wheel vehicles were plotted against vehicle speed, and outliers were removed.
- From the individual functions, an average function was determined for each vehicle category.

Average-speed functions were derived for each pollutant (CO, HC, NO_x and 'ultimate CO_2') and each vehicle category.

The emission functions for a certain vehicle category were used to predict the emissions for test cycles for which no measurement results were available.

Hot emission factors were then derived for three levels of detail:

- Emission factors for 'traffic situations' to estimate emissions from road vehicles on a small spatial scale, for detailed inventories, or impact studies.
- Aggregated emission factors for urban, rural and motorway driving. This type of output may be used for less detailed impact studies (*e.g.* inventories on a regional or national level).
- Average-speed emission functions for situations where no detailed information is available on driving patterns, but information is available on traffic flow and average speed.

The emission factors of the different levels of detail had to be consistent, and were therefore developed using the same input (real-world data and emission test results) and methodology.

B6.5.2 Traffic situation model

One modelling approach used in the ARTEMIS work on road transport is based on 'traffic situations' (André and Poize, 2002). The following three steps are required by this approach, and each of these steps is discussed in more detail in the paragraphs which follow:

(i) The determination of the traffic situation scheme (*i.e.* which traffic situations are relevant for road transport in general, and for two-wheel vehicles in particular).

(ii) The identification of driving patterns for two-wheel vehicles which are representative of the identified traffic situations.

(iii) The derivation of corresponding emission factors for each vehicle category.

Traffic situation scheme

A traffic situation scheme was agreed for road transport in ARTEMIS and COST346 (André *et al.* 2006; Sturm *et al*., 2006). The categorisation is divided in urban and rural locations, and the types of roads that are available at both locations - ranging from wide motorways to small roads in town centres and residential areas. In addition, parameters such as the speed limit range, gradient and 'sinuosity' (the number of curves in the road) were addressed. The traffic situations which were used for two-wheel vehicles in ARTEMIS are provided in **Table B6-8**.

Table B6-8: Overview of the defined traffic situations employed in ARTEMIS

Road category	Road type	Curvature	Speed limit range km/h[32]	Traffic condition
Urban	Motorway	Low	60-130	Night-time, Off-peak, Peak hours, Stop-and-go
	Primary Road	Low	50-110	Night-time, Off-peak, Peak hours, Stop-and-go
	Secondary Road	Low	50-80	Night-time, Off-peak, Peak hours, Stop-and-go
	Collector Road	Low	50	Night-time, Off-peak, Peak hours, Stop-and-go
	Residential Street	Low	30-50	Night-time, Off-peak, Peak hours, Stop-and-go
Rural	Motorway	Low	60-130	Free-flow, Heavy, Saturated, Stop-and-go
	Primary Road	Low	50-110	Free-flow, Heavy, Saturated, Stop-and-go
	Secondary Road	Curved, Low	50-100	Free-flow, Heavy, Saturated, Stop-and-go
	Collector Road	Curved, Low	50-80	Free-flow, Heavy, Saturated, Stop-and-go

[32] Speed limits exist for each 10 km/h step in the stated range.

Driving pattern selection

For selecting real-world driving patterns which were representative of the identified traffic situations, the main source of data was the IMMA measurement programme for the development of the WMTC. Data from the FHB study (Czerwinski, 1995), and on-road measurements performed by the University of Darmstadt (Schröder, 2000), were also used. The procedure that was applied in ARTEMIS for HDVs (Rexeis *et al.*, 2005; Sturm *et al*., 2006) to select representative driving patterns for the traffic situations was also adopted for two-wheel vehicles. This work was conducted by RWTÜV. For all driving patterns in the database the vehicle speed, the normalised engine speed, the engine load and, if possible, the road gradient were plotted against time. The engine speed was normalised to the difference between the rated speed and the idling speed. The engine load was calculated by dividing the actual power by the maximum power at the actual engine speed. This calculation required the full-load power curves of the engine. The vehicle speed pattern was then manually separated into 'homogeneous' parts representing a particular road type/traffic situation. Appropriate vehicle speed patterns were assigned to the different cells of the traffic situation classification matrix.

Emission factor calculation

For each vehicle, the available on-line emission data were processed to give an emission function relating to average running speed. The emission functions of the vehicles belonging to a given vehicle category were grouped and the average function was determined. The emission factors for a given vehicle category and traffic situation were calculated using the relevant emission function and the second-by-second speed of the driving pattern for the traffic situation. In **Figure B6-1** the CO, HC, NO_x and ultimate CO_2 emission factors are shown for Pre-Euro I, Euro I, Euro II and Euro III legislation classes of four-stroke motorcycles with an engine capacity between 250 and 750 cm^3, and for the different traffic situations.

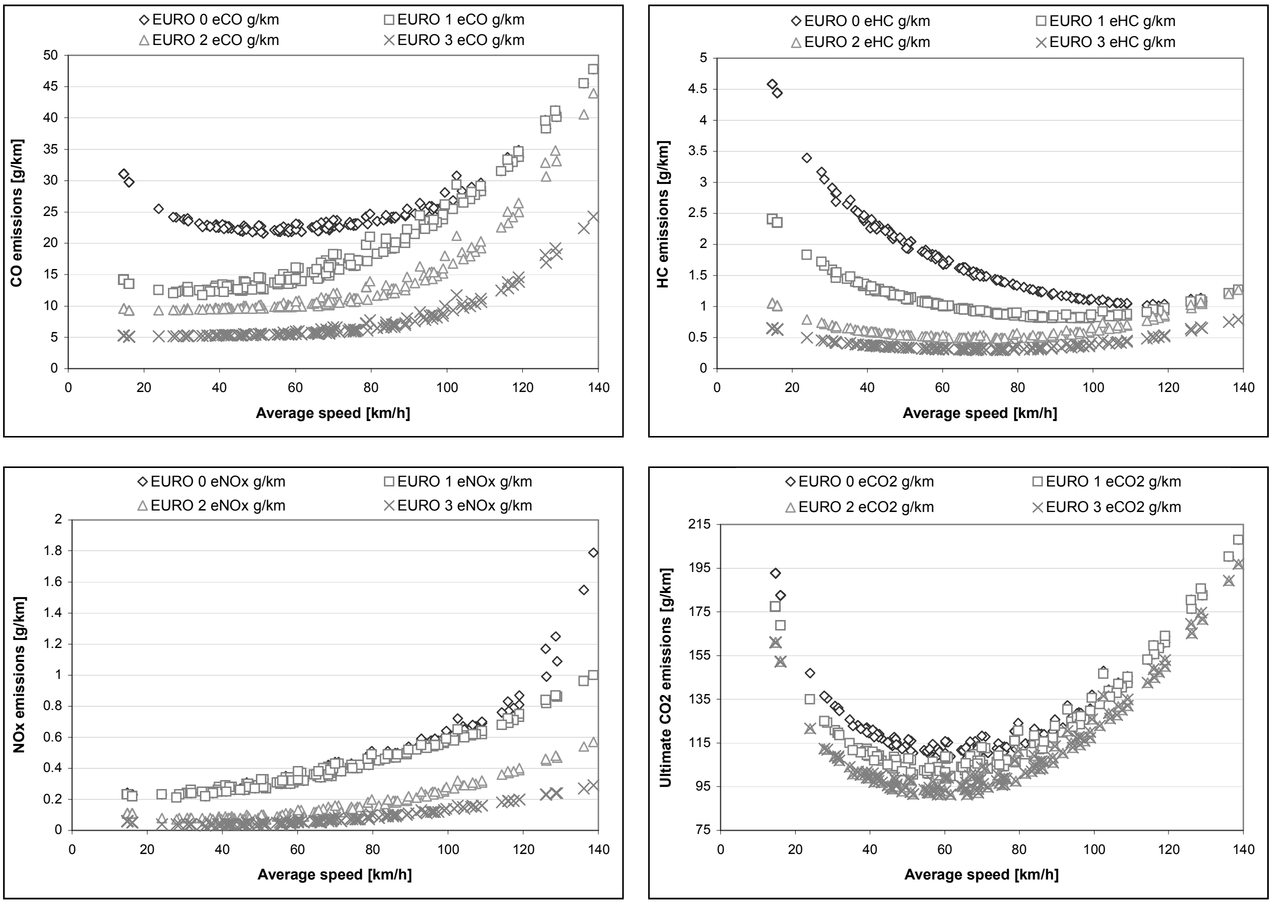

Figure B6-1: Emission factors for traffic situations for four-stroke 250-750 cm^3 motorcycles

The following main conclusions were drawn from plots such as those provided in **Figure B6-2**:

- Reductions in emissions of CO, HC and NO_x were observed for more stringent emission limits.
- The modelling methodology provides emission factors for traffic situations. This method does not fully take into account the differences in the emissions for test cycles having similar levels of average speed but relatively high

differences with respect to driving dynamics (average acceleration, RPA, *etc.*). However, it offers significant improvements compared with an average-speed model. Nevertheless, a better representation of driving dynamics might be achieved by adding other parameters, although this was beyond the scope of ARTEMIS.

Emission factors were derived for all the identified traffic situations and vehicle categories (giving a total of 5,280 traffic situation emission factors). The emission factors for these classes are provided in the overall ARTEMIS emission model.

B5.5.3 Urban, rural and motorway emission factors

In addition to providing emission factors for the identified traffic situations, more aggregated emission factors were developed for use in national or international emission inventories. Using expert judgement, traffic situations were selected which were most likely to be representative of average urban, rural and motorway driving. The emission factors derived using this approach were consistent with the emission factors derived for the traffic situations. The traffic situations given in **Table B6-9** were selected to determine the average urban, rural and motorway emission factors. The corresponding emission factors are given by Elst *et al.* (2006).

Table B6-9: Traffic situations representative of urban, rural and motorway driving.

Area type	Road type	Speed limit (km/h)	Gradient type	Traffic condition
Rural	Motorway	120	No gradient	Heavy
Rural	Motorway	120	No gradient	Free-flow
Rural	Primary road	90	No gradient	Free-flow
Rural	Secondary road	90	No gradient	Free-flow
Urban	Motorway	70	No gradient	Off-peak
Urban	Primary road	50	No gradient	Off-peak

B6.5.4 Average-speed model

In order to deliver consistent emission factors, the average-speed functions were based on the results of the traffic situation approach. For each vehicle category and pollutant the average speed function was determined by fitting a regression model (up to fifth order polynomial) to the traffic situation emission factors using the least squares method.

$$E = a_5 * v^5 + a_4 * v^4 + a_3 * v^3 + a_2 * v^2 + a_1 * v + a_0 \quad \text{(Equation B6-2)}$$

Where: E is the emission factor in g/km
v is the vehicle speed in km/h
a_0 to a_5 are coefficients

The values of the coefficients for different pollutants and vehicle categories are given in **Tables B6-10** and **B6-11**.

B6.5.5 Other topics

Within ARTEMIS measurements were conducted to address the effects of cold starting and fuel properties on emissions. The effects of inspection and maintenance were also examined using the results from the CITA study (Elst, 2002), in which emission measurements were conducted before and after maintenance.

Cold-start emissions

The cold-start emission factors were determined by using all available data for the relevant vehicle categories defined in ARTEMIS. Fuel consumption increases for most two-wheel vehicles as result of a cold start. No clear relationships between the categories was observed. For this reason, cold-start values for fuel consumption the only distinction drawn was that between two- and four-stroke vehicles. Although the most relevant categories were included in the sample, for some categories there was still a lack of data. For these categories cold-start emissions were estimated based on observed trends and expert judgement. The additional emissions for cold start are given in **Table B6-12**.

Table B6-10: CO and HC emissions as function of average speed.

Engine capacity (cm^3)	Engine type	Legislative category	a_5	a_4	a_3	a_2	a_1	a_0

CO (g/km)								
<= 150	2-stroke	Pre-Euro I	-0.0000000160	0.0000051640	-0.0006477680	0.0439720310	-1.520	35.97
		Euro I	-0.0000000100	0.0000034090	-0.0004276220	0.0290263320	-1.003	23.73
		Euro II	-0.0000000080	0.0000026800	-0.0003362310	0.0228435880	-0.791	18.75
		Euro III	-0.0000000040	0.0000015190	-0.0001904000	0.0128754100	-0.443	10.40
	4-stroke	Pre-Euro I	-0.0000000130	0.0000046610	-0.0006357700	0.0468953390	-1.792	42.06
		Euro I	-0.0000000130	0.0000042670	-0.0005156470	0.0345460700	-1.190	26.21
		Euro II	-0.0000000070	0.0000023270	-0.0003035930	0.0212606280	-0.728	13.03
		Euro III	-0.0000000040	0.0000012820	-0.0001673260	0.0117188370	-0.401	7.18
150-250	2-stroke	Pre-Euro I	-0.0000000100	0.0000043650	-0.0007174840	0.0594319480	-2.533	63.41
		Euro I	-0.0000000100	0.0000043650	-0.0007174840	0.0594319480	-2.533	63.41
		Euro II	-0.0000000080	0.0000034390	-0.0005656170	0.0468916170	-2.000	50.13
		Euro III	-0.0000000040	0.0000019050	-0.0003132360	0.0259481360	-1.106	27.69
	4-stroke	Pre-Euro I	-0.0000000030	0.0000013860	-0.0002338510	0.0226837210	-1.041	27.21
		Euro I	-0.0000000030	0.0000013860	-0.0002338510	0.0226837210	-1.041	27.21
		Euro II	-0.0000000020	0.0000011060	-0.0001864480	0.0180439600	-0.827	21.55
		Euro III	-0.0000000010	0.0000005980	-0.0001012820	0.0098607080	-0.454	11.87
250-750	4-stroke	Pre-Euro I	-0.0000000060	0.0000032020	-0.0005430050	0.0442915060	-1.743	48.58
		Euro I	-0.0000000010	0.0000008420	-0.0001363800	0.0125591790	-0.493	18.98
		Euro II		0.0000003130	-0.0000487950	0.0034915840	-0.103	10.39
		Euro III		0.0000001760	-0.0000273550	0.0019526440	-0.057	5.74
> 750	4-stroke	Pre-Euro I	-0.0000000100	0.0000043670	-0.0007403330	0.0630370720	-2.679	63.98
		Euro I	-0.0000000120	0.0000048320	-0.0006899920	0.0457671170	-1.486	29.85
		Euro II		0.0000003310	-0.0000718320	0.0077326010	-0.402	9.72
		Euro III		0.0000001850	-0.0000398780	0.0042745450	-0.222	5.36
HC (g/km)								
<= 150	2-stroke	Pre-Euro I	-0.0000000130	0.0000047140	-0.0006418160	0.0456813730	-1.7469	35.60
		Euro I	-0.0000000030	0.0000011070	-0.0001585700	0.0124622060	-0.5223	11.19
		Euro II	-0.0000000010	0.0000005580	-0.0000807660	0.0064315100	-0.2728	5.90
		Euro III	-0.0000000010	0.0000003830	-0.0000544650	0.0042273920	-0.1752	3.72
	4-stroke	Pre-Euro I		0.0000003320	-0.0000539140	0.0046576050	-0.2170	5.16
		Euro I		0.0000002830	-0.0000428550	0.0034132770	-0.1465	3.54
		Euro II		0.0000002350	-0.0000311550	0.0020926800	-0.0721	1.45
		Euro III		0.0000001590	-0.0000211530	0.0014129890	-0.0481	0.94
150-250	2-stroke	Pre-Euro I	-0.0000000080	0.0000036630	-0.0006076830	0.0500921190	-2.2304	51.89
		Euro I	-0.0000000080	0.0000036630	-0.0006076830	0.0500921190	-2.2304	51.89
		Euro II	-0.0000000040	0.0000019490	-0.0003233790	0.0266492790	-1.1860	27.57
		Euro III	-0.0000000020	0.0000012250	-0.0002029090	0.0166945360	-0.7417	17.22
	4-stroke	Pre-Euro I		0.0000001630	-0.0000282700	0.0025148750	-0.1189	2.89
		Euro I		0.0000001630	-0.0000282700	0.0025148750	-0.1189	2.89
		Euro II		0.0000001000	-0.0000168580	0.0014561010	-0.0667	1.57
		Euro III		0.0000000610	-0.0000104440	0.0009070400	-0.0416	0.98
250-750	4-stroke	Pre-Euro I		0.0000003620	-0.0000648730	0.0057914610	-0.2808	7.66
		Euro I		0.0000001880	-0.0000328180	0.0029011230	-0.1401	3.95
		Euro II		0.0000001010	-0.0000168560	0.0014372490	-0.0651	1.75
		Euro III		0.0000000540	-0.0000092500	0.0008121360	-0.0381	1.06
> 750	4-stroke	Pre-Euro I		0.0000003290	-0.0000568030	0.0051651880	-0.2647	7.69
		Euro I		0.0000002940	-0.0000514520	0.0044797230	-0.2053	4.74
		Euro II		0.0000001460	-0.0000259190	0.0022362350	-0.0962	1.97
		Euro III		0.0000000940	-0.0000165170	0.0014088330	-0.0600	1.22

Table B6-11: NO_x and CO_2 emissions as function of average speed.

Engine capacity (cm^3)	Engine type	Legislative category	a_5	a_4	a_3	a_2	a_1	a_0

NO_x (g/km)

<= 150	2-stroke	Pre-Euro I		0.0000001000	-0.0000107250	0.0005281520	-0.011591	0.113403
		Euro I		0.0000000080	-0.0000008270	0.0000468360	-0.001231	0.050418
		Euro II		0.0000000660	-0.0000073980	0.0003864250	-0.009018	0.117084
		Euro III		0.0000000100	-0.0000018720	0.0001302210	-0.003540	0.049698
	4-stroke	Pre-Euro I		0.0000001360	-0.0000154050	0.0008232260	-0.016964	0.348381
		Euro I		0.0000002090	-0.0000234580	0.0012349710	-0.026326	0.436783
		Euro II		0.0000001140	-0.0000127520	0.0007340340	-0.018969	0.400983
		Euro III		0.0000000590	-0.0000068590	0.0004079500	-0.010901	0.219131
150-250	2-stroke	Pre-Euro I		0.0000000220	-0.0000020240	0.0000881630	-0.002018	0.056336
		Euro I		0.0000000220	-0.0000020240	0.0000881630	-0.002018	0.056336
		Euro II		0.0000000360	-0.0000040250	0.0002143630	-0.005570	0.094118
		Euro III		0.0000000140	-0.0000013940	0.0000644640	-0.001415	0.030817
	4-stroke	Pre-Euro I		0.0000000330	-0.0000048120	0.0003487520	-0.009007	0.294864
		Euro I		0.0000000330	-0.0000048120	0.0003487520	-0.009007	0.294864
		Euro II		0.0000000330	-0.0000048120	0.0003487520	-0.009007	0.294864
		Euro III		0.0000000160	-0.0000024260	0.0001809710	-0.004924	0.157350
250-750	4-stroke	Pre-Euro I	0.0000000005	-0.0000001664	0.0000191082	-0.0009296045	0.020208	0.085372
		Euro I	0.0000000001	-0.0000000174	0.0000014062	0.0000198110	-0.001793	0.245362
		Euro II		0.0000000050	-0.0000010500	0.0001386210	-0.006920	0.186235
		Euro III		0.0000000080	-0.0000012960	0.0001181480	-0.004822	0.106721
> 750	4-stroke	Pre-Euro I	0.0000000001	-0.0000000513	0.0000076394	-0.0004643247	0.011418	0.039434
		Euro I		0.0000000120	-0.0000019880	0.0002356690	-0.011038	0.305914
		Euro II		-0.0000000036	0.0000002877	0.0000990898	-0.008524	0.275363
		Euro III		0.0000000003	-0.0000002087	0.0000775314	-0.005274	0.152659

CO_2 (g/km)

<= 150	2-stroke	Pre-Euro I	-0.000000109	0.0000366920	-0.0049149110	0.3486095640	-13.00	280.07
		Euro I	-0.000000101	0.0000338220	-0.0045312140	0.3214645280	-11.99	258.40
		Euro II	-0.000000101	0.0000338220	-0.0045312140	0.3214645280	-11.99	258.40
		Euro III	-0.000000101	0.0000338220	-0.0045312140	0.3214645280	-11.99	258.40
	4-stroke	Pre-Euro I	-0.000000148	0.0000477800	-0.0060094270	0.3838718320	-12.29	241.17
		Euro I	-0.000000122	0.0000392920	-0.0049417780	0.3156535440	-10.11	198.26
		Euro II	-0.000000108	0.0000354720	-0.0045484620	0.2953465350	-9.72	188.94
		Euro III	-0.000000108	0.0000354720	-0.0045484620	0.2953465350	-9.72	188.94
150-250	2-stroke	Pre-Euro I	-0.000000064	0.0000275310	-0.0045724950	0.3863983840	-16.95	399.55
		Euro I	-0.000000064	0.0000275310	-0.0045724950	0.3863983840	-16.95	399.55
		Euro II	-0.000000064	0.0000275310	-0.0045724950	0.3863983840	-16.95	399.55
		Euro III	-0.000000064	0.0000275310	-0.0045724950	0.3863983840	-16.95	399.55
	4-stroke	Pre-Euro I	-0.000000036	0.0000152460	-0.0024954910	0.2087500410	-8.77	210.49
		Euro I	-0.000000036	0.0000152460	-0.0024954910	0.2087500410	-8.77	210.49
		Euro II	-0.000000036	0.0000152460	-0.0024954910	0.2087500410	-8.77	210.49
		Euro III	-0.000000036	0.0000152460	-0.0024954910	0.2087500410	-8.77	210.49
250-750	4-stroke	Pre-Euro I	-0.000000050	0.0000221070	-0.0036650260	0.3039889110	-12.68	323.19
		Euro I	-0.000000039	0.0000172940	-0.0029498740	0.2567738600	-11.20	294.54
		Euro II	-0.000000039	0.0000172230	-0.0029103240	0.2489848870	-10.61	270.85
		Euro III	-0.000000039	0.0000172230	-0.0029103240	0.2489848870	-10.61	270.85
> 750	4-stroke	Pre-Euro I	-0.000000057	0.0000254170	-0.0042908690	0.3628231760	-15.35	386.22
		Euro I	-0.000000056	0.0000248560	-0.0042236220	0.3596414580	-15.51	391.60
		Euro II	-0.000000058	0.0000256370	-0.0043411290	0.3686075710	-15.73	386.41
		Euro III	-0.000000058	0.0000256370	-0.0043411290	0.3686075710	-15.73	386.41

Table B6-12: Excess cold-start emission per category.

Engine type	Engine capacity (cm^3)	Legislative category	CO (g)	HC (g)	NO_x (g)	FC [33] (cm^3)	Ultimate CO_2 [34] (g)
2-stroke	<50	Pre-Euro I	4	6	0.0	9	20
		Euro I	4	6	0.0	9	20
		Euro II	4	6	0.0	9	20
		Euro III	4	6	0.0	9	20
	50-150	Pre-Euro I	4	6	0.0	9	20
		Euro I	4	6	0.0	9	20
		Euro II	4	6	0.0	9	20
		Euro III	4	6	0.0	9	20
	151-250	Pre-Euro I	4	6	0.0	9	20
		Euro I	4	6	0.0	9	20
		Euro II	4	6	0.0	9	20
		Euro III	4	6	0.0	9	20
	251-750	Pre-Euro I	4	6	0.0	9	20
		Euro I	4	6	0.0	9	20
		Euro II	4	6	0.0	9	20
		Euro III	4	6	0.0	9	20
4-stroke	<50	Pre-Euro I	5.0	1.3	0.10	17	40
		Euro I	4.5	1.2	0.15	17	40
		Euro II	4.0	1.1	0.20	17	40
		Euro III	3.5	1.0	0.25	17	40
	50-150	Pre-Euro I	5.0	1.3	0.10	17	40
		Euro I	4.5	1.2	0.15	17	40
		Euro II	4.0	1.1	0.20	17	40
		Euro III	3.5	1.0	0.25	17	40
	151-250	Pre-Euro I	5.0	1.3	0.10	17	40
		Euro I	4.5	1.2	0.15	17	40
		Euro II	4.0	1.1	0.20	17	40
		Euro III	3.5	1.0	0.25	17	40
	251-750	Pre-Euro I	22	3.5	0.06	17	40
		Euro I	20	3.0	0.09	17	40
		Euro II	18	2.5	0.12	17	40
		Euro III	16	2.0	0.15	17	40
	>750	Pre-Euro I	22	3.5	0.06	17	40
		Euro I	20	3.0	0.09	17	40
		Euro II	18	2.5	0.12	17	40
		Euro III	16	2.0	0.15	17	40

Fuel properties

The emission model can be used to estimate emissions for trade fuel and fuel meeting the future WWFC4 requirements. Similar factors are applied to two- and four-stroke engines, and CO, HC, ultimate CO_2 and fuel consumption. For NO_x a distinction is made with regard to engine type. The factors to be applied to address the effects of fuel properties are given in **Table B6-13**.

Table B6-13: Factors to be applied on standard emission factors to address the effects of fuel.

Fuel	Engine type	CO (%)	HC (%)	NO_x (%)	FC and ultimate CO_2 (%)
Trade fuel	2-stroke	100%	100%	100%	100%
	4-stroke	100%	100%	100%	100%
WWFC4 fuel	2-stroke	85%	95%	85%	100%
	4-stroke	85%	95%	110%	100%

[33] Fuel consumption is calculated applying the carbon balance method (using *measured* CO_2, CO and HC emissions)
[34] CO_2 emissions based on fuel consumption - *not exhaust* CO_2 - assuming that all molecules containing carbon are oxidised to CO_2.

Inspection and maintenance

For seven vehicles measurements were carried out before and after maintenance. The results were divided according to the type of maintenance that was conducted. However, this approach could not be applied in the emission model due to a lack on real-world data on types of maintenance.

The additional emissions to be applied to address the effect of inspection and maintenance are given in **Table B6-14**. The factors in **Table B6-14** have to be applied to the estimated share of vehicles that need maintenance.

Table B6-14: Factors to be applied on the standard emission factors to address the effect of inspection and maintenance.

	CO (%)	HC (%)	NO_x (%)	FC and ultimate CO_2 (%)
Effect of inspection and maintenance	115%	112%	130%	111%

B6.6 Summary, conclusions and recommendations

B6.6.1 Summary and conclusions

Real-world test cycles

- Since only a limited amount of real-world motorcycle driving data were available for ARTEMIS, it was decided to evaluate the available test cycles for the purpose of deriving representative emission values for two-wheel vehicles, rather than developing a new dedicated test cycle.
- Only two existing test cycles were based on on-road measurements conducted on motorcycles (FHB test cycles and the WMTC).
- When real-world passenger car and motorcycle driving were compared, the main differences were at higher average speeds. At higher speeds the driving of two-wheel vehicles is much more dynamic than that of passenger cars due to the relatively high power:mass ratio.
- The CADC for passenger cars is very dynamic, and for urban driving has appropriate values of RPA and average acceleration for motorcycles.
- The dynamics of the FHB Zentrum cycle are similar to those of the CADC urban and the original WMTC part 1, but the dynamics of the other FHB cycles are lower than those of the CADC and original WMTC test cycle. This is probably due to the type of motorcycle that was used for the on-road recordings carried out by FHB.
- Since the CADC showed the best relationship with real-world motorcycle driving, and because the WMTC test cycle was not available for the project, the CADC test cycle was included in the main measurement programme of ARTEMIS. In addition, the real-world test cycles of FHB were included in order to get an indication of the emissions produced during test cycles that originate from speed-time data recorded with a motorcycle.

Vehicle categorisation

- Two-wheel vehicles were categorised by taking into account engine capacity, engine type and the presence of a catalyst. Furthermore, age and model class were used. Available fleet data were used for selecting vehicles for the ARTEMIS measurement programme.
- The vehicle categorisation in the emission model is in line with the one used within the HBEFA model and the vehicle classification proposed for the Global Technical Regulation (GTR) that contains the WMTC test cycle.

Round-robin test programme

The conclusions of the round-robin programme were presented in Section B6.2.3.

Main measurement programme

- In total, 115 motorcycles were tested according to the measurement protocol. Sixty vehicles were tested at TNO-Automotive, forty-five at TÜV-Nord and ten at KTI. Since the tests were carried out in 2002, only vehicles that complied with emission limits prescribed in Directive 97/24/EC Stage 1 and ECE Regulation R40 were tested. 62% of the vehicles complied with Directive 97/24/EC Stage 1 limits. and 12% of the motorcycles tested were equipped with a catalyst. Engine capacity classes 51-150 cm^3 (27%) and 751-1000 cm^3 (21%) dominated the fleet.

- The participants noted that it was difficult to obtain small two-stroke scooters that were equipped with direct-injection systems and oxidation catalysts.
- NO_x emissions from two-wheel vehicles were very low over the type approval cycle.
- For motorcycles having high CO and HC emission results, the differences between the results over the type approval and real-world cycles were negligible. As emission levels over the type approval test decrease, the differences are increasing. This conclusion is not valid for NO_x. Some of the tested motorcycles were equipped with an exhaust system configuration which appeared to have been specifically calibrated for the type approval cycle.
- Emissions over the CADC urban and rural parts were higher than emissions over the FHB test cycles, and it appeared that the differences were related to driving dynamics. However, for motorcycles equipped with exhaust gas after-treatment systems (Euro III), driving dynamics appears to be a less reliable determinant of emissions.

Cold-start emissions

- Cold-start emission factors were calculated using the results over the pre-conditioning cycles used for type approval. There were wide variations in cold-start emissions, even within a vehicle category. For some motorcycles, negative cold-start emission factors were observed for CO and HC.
- As the emission limit decreased, the contribution of the cold-start CO and HC to the total emissions increased. NO_x emissions appeared to increase for newer vehicles with lower cold-start CO and HC emissions.

Effects of fuel properties

- For the measurements in ARTEMIS an existing (Hungarian) market fuel and a fuel meeting the WWFC Category 4 future requirements were selected.
- Based on the results from the five motorcycles tested, the following main conclusions were drawn with respect to replacing market fuel by fuel that is compliant with WWFC4 requirements:
  - CO emissions were, on average, reduced by 15%.
  - HC emissions decreased by 5%.
  - NO_x emissions were not affected.
  - CO_2 emissions increased by 4%.
  - Fuel consumption was not affected.

Effects of inspection and maintenance

- 105 motorcycles were tested over loaded and idle tests. Of these, nine motorcycles had difficulty complying with the Type I and Type II emission limits in Directive 97/24/EC and ECE Regulation 40. In reality, this number might be even higher, since most of the motorcycles that were tested were provided by dealers and national importers.
- For seven of the motorcycles technical inspection or maintenance could be carried out. For two motorcycles extensive repairs were needed.
- For one motorcycle maintenance had an adverse effect, with increases in emissions of between 1% and 18%, depending on the pollutant. For specific repairs, such as the replacement of a faulty battery, large improvements in emissions were observed. The effect of specific inspection and maintenance on emissions should therefore not be neglected.

Emission modelling

- The ARTEMIS model was based on large numbers of bag and on-line emission measurements. In total, about 2,700 emission results were available for emission modelling. Compared with the information that was previously used in former two-wheel vehicles emission models, this represents an enormous amount of data.
- A significant number of emission measurements from external sources were added to the ARTEMIS database, but the database contained only a few emission results for Euro II and Euro III motorcycles. Therefore, it was decided to use weighting factors based on legislative emission limits to increase the amount of data for the most modern vehicles.
- The modelling methodology that was developed for the HBEFA model was also employed for ARTEMIS, including the vehicle categorisation.
- The ARTEMIS model is able to provide hot emission factors for several vehicle categories at three levels of output: (i) emission factors for 'traffic situations' to estimate emissions from road vehicles on a small spatial scale, (ii) aggregated emission factors for urban, rural and motorway driving, and (iii) average-speed emission functions for situations where no detailed information is available on driving patterns.
- Average factors to address the effects on the emissions of cold starting were based on observed trends and expert judgement;
- The effects of fuel properties on emissions were addressed in the model by using the average results of the measurements conducted by KTI.

- Average adjustment factors were derived to address the effects of different types of inspection and maintenance on emissions.

B6.6.2 Recommendations

The work conducted within ARTEMIS addressed a wide range of different topics relating to emissions from two-wheel vehicles. Nevertheless, a number of issues remain for future investigation, and some recommendations are given below.

Real-world test cycles

- At present, real-world driving data are limited to certain types of two-wheel vehicle and traffic situation. Real-world data should be recorded for a wider variety of vehicles to obtain more representative driving patterns for specific traffic situations.

Vehicle categorisation

- Significant improvements have recently been achieved with regard to statistics on the European two-wheel vehicle fleet. Several sources are currently available on the internet, but the most detailed information can be obtained from ACEM.
- A detailed system of vehicle categorisation can be defined for in-use motorcycle. However, the more detailed the categorisation the more vehicles need to be measured to obtain emission robust factors. Therefore, it is recommended that the actual categorisation is adapted to the number of available emission results.

Round-robin test programme

Recommendations from the round-robin programme were presented in Section B6.2.3.

Main measurement programme

- A detailed measurement protocol - which defines the measurement procedure - and a standard test report template are vital for assuring comparability of measurements carried out by different laboratories. The presence of a test-witness who is aware of the measurement procedure and preparative actions, bag analysis and data processing could even improve quality and comparability of the results.
- It is recommended that test drivers become acquainted with the test cycle and the specific behaviour of the two-wheel vehicle to be tested.
- It proved difficult to obtain motorcycles from private users for the main measurement programme. Dealers, rental companies and importers proved to be more co-operative. Two-wheel vehicles obtained from dealers, rental companies and importers are, however, generally well maintained and relatively new. Such vehicles are not recommended when addressing topics such as tampering or deterioration.

Cold-start emissions

- For certain vehicle categories, additional measurements are required to obtain an indication of cold-start emissions. The data obtained from the main measurement programme of ARTEMIS provide a solid basis, but should be extended to address the effects for vehicle classes for which few results are available (small two-wheel vehicles and vehicles that comply with Euro II and Euro III emission limits).

Effect of fuel properties

- A dedicated measurement programme should be developed to further address this topic. The measurement programme should begin by evaluating the fuels that are on the European market. From this assessment, fuels should be selected that are different with regard to specific parameters, and emission tests should be conducted.

Effect of inspection and maintenance

- In order to obtain a more detailed understanding of this topic, a dedicated test programme should be conducted. The programme should involve measurements before and after maintenance on a significant number of motorcycles. In addition, a distinction might be made between vehicle categories and types of maintenance.
- Another issue of importance might be deterioration of the vehicle (effect of mileage on emissions).

Emission modelling

- Ideally, an emission modelling methodology should be developed before actual emission measurements take place in order to provide the necessary input data. The methodology applied within HBEFA and the ARTEMIS emission model is based on on-line and bag emission results. Further on-line measurements would improve the output of the emission model significantly. In addition, bag results for short test cycles would provide additional information for validation.
- For a number of vehicle categories and traffic situations, the 'representative' driving pattern was based on data recorded

for another vehicle category or traffic situation. Additional real-world measurements would improve the output of the emission model for these vehicle categories.

- Due to the lack of emission data for current and future emission categories (Stage 2 and Stage 3), the output of the emission model will improve significantly when both on-line and bag emission measurements are conducted on vehicles compliant with the legislation.

B6.7 References

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B7 COLD-START EMISSIONS (PASSENGER CARS)

B7.1 Introduction

Prior to ARTEMIS, three main methods were available in Europe for modelling cold-start emissions:

- The Handbook of Emission factors (HBEFA), applied mainly in Germany and Switzerland (Keller *et al.*, 1995).
- The MEET approach (Joumard and Serié, 1999; European Commission, 1999).
- The COPERT III approach (Ntziachristos and Samaras, 2000), which relies in part upon MEET.

Such models are necessary for large-scale applications such as national inventories, but could also be used for smaller scale applications. The geographical and temporal boundaries of the application depend upon the quality of the available input data.

Samaras *et al.* (2001) evaluated the cold-start emission values predicted using the three approaches. Due to the methodological differences between COPERT III and MEET, there were discrepancies between the predicted values. However, the differences were mostly observed at very low speeds and ambient temperatures. The differences were lower at temperatures between 15°C and 25°C, and also at high vehicle speeds. The agreement between the results from COPERT III and HBEFA was very good, especially given the differences in methodology.

One of the tasks of ARTEMIS was to develop an improved empirical model for cold-start excess emissions from passenger cars, including parameters such as the pollutant, the vehicle type and the driving conditions, and using all the existing data in Europe. Cold-start measurements collected during the MEET project, measurements collected after MEET, and measurements carried out specifically for the ARTEMIS study were used. The ARTEMIS work was reported by André and Joumard (2005) and Joumard *et al.* (2007), and this Section of Part B provides a summary.

B7.2 The concept of cold-start excess emissions

As long as a vehicle does not reach its full running temperature, emissions of atmospheric pollutants (CO, HC, NO_x, PM) are elevated (Duboudin and Crozat, 2002). In the case of cars without a three-way catalyst, the excess emission is a result of non-optimal engine running, and the engine temperature is the most important parameter. In the case of vehicles equipped with a three-way catalyst, the catalyst temperature also needs to be taken into account.

The evolution in time of the instantaneous exhaust emission of a vehicle, for a given pollutant, engine speed and initial engine temperature, can be split up into an initial cold-start phase - with a decreasing emission due to the progressive increase in the engine (and catalyst) temperature - followed by a stable phase when the normal 'hot' engine temperature is reached (**Figure B7-1**). The duration of the initial cold-start phase, $\boldsymbol{t_{cold}}$, is shown on the *x*-axis in **Figure B7-1**. The definition can also be stated in terms of distance, whereby the distance (***d***) needed to reach stabilised emissions is $\boldsymbol{d_{cold}}$.

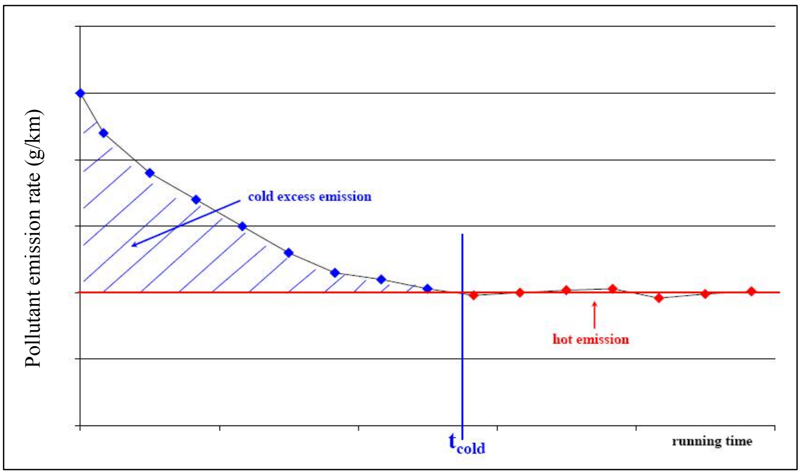

Figure B7-1: Evolution of the instantaneous emission of a pollutant as a function of time.

The emission profile in **Figure B7-1** is, of course, idealised. During a driving cycle composed of a succession of different vehicle speeds and engine speeds, the instantaneous emission profile is much more complicated. It depends upon the different running phases and on the progressive temperature increase, with vehicle and engine speed variations being much more rapid than the temperature changes.

The total exhaust emission over a driving cycle can therefore be calculated as the sum of the hot emission during the cycle and the cold-start excess emission:

$$E_{total}\,(g) = E_{hot}\,(g) + E_{cold}\,(g) \qquad \text{(Equation B7-1)}$$

The cold-start excess emission is defined as the total amount of the pollutant emitted between the start time ($t = 0$) and time t_{cold}, minus the amount of pollutant which would be emitted by the vehicle at its normal running temperature during the same time period.

Normally, the total cold-start excess emission is obtained as the difference between the total emission measured over a given driving cycle with a cold start, and the total emission over the same cycle with a hot start. In order to collect the full cold-start excess emission, the overall driving cycle must be long enough for the stabilisation distance to be reached. The excess emission depends on the pollutant, the ambient temperature and the driving cycle. However, to determine t_{cold} or d_{cold} as a function of the driving cycle, the duration of sub-cycles must be much shorter than t_{cold}. Hence, short cycles of 100-200 seconds have been developed (Joumard *et al.,* 1995), and these are repeated in succession on the chassis dynamometer. In fact, a vehicle can start at any temperature, and not just the ambient temperature. The cold-start excess emission can therefore be defined in terms of the actual initial engine and catalyst temperatures. Similarly, a vehicle is not always driven over the full cold-start distance d_{cold}, and the excess emission can also be defined in terms of the actual distance travelled under cold-start conditions.

A ‘relative’ cold-start emission can also be defined. This is the ratio between the cold emission during a given driving cycle and the hot emission during the same cycle. This ratio depends upon the distance travelled, as the cold-start emission decreases with distance and the hot emission (under steady-state conditions) is constant with distance.

There are actually five different ways of representing cold-start emissions:

- An average total emission factor (in g/km) for the cold-start period, including the hot emissions.
- An absolute total emission (in g) for the cold-start period, including the hot emissions.
- The difference between the average emission factors (in g/km) for the cold-start and hot periods (*i.e.* a unit excess emission).
- The ratio between the cold-start and hot emissions (relative cold-start emission).
- An absolute excess cold-start emission (in g), defined as the additional emission value obtained under cold-start conditions compared with the emission value that would have been recorded for the same period (or cycle) under hot-start conditions.

In this report, the last definition is used.

B7.3 Methodology

B7.3.1 Database

Cold-start emissions data for passenger cars were obtained from several European laboratories. The cars were divided into ten categories, for which emission data for regulated pollutants (RP) and unregulated pollutants (URP) were available:

- Pre-Euro I petrol without a catalyst (RP and URP)
- Pre-Euro I diesel without a catalyst (URP)
- Pre-Euro I petrol with a catalyst (RP)
- Euro I petrol (RP and URP)
- Euro I diesel (RP and URP)
- Euro II petrol (RP and URP)
- Euro II diesel (RP and URP)
- Euro III petrol (RP and URP)
- Euro III diesel (RP and URP)
- Euro IV petrol (RP and URP)

Five types of cold-start and hot-start cycle were used (**Table B7-1**), although not all cycles were used to test all vehicles. Each of the short INRETS cycles was repeated 15 times. These cycles were developed from 23,000 km of driving measurements recorded in France using 35 private cars (André, 1989; André, 1998; Joumard *et al.*,1999). The ARTEMIS urban cycle was developed by André (2004a, b).

Table B7-1: Main characteristics of the driving cycles used.

Type	Name	Short name	Duration (s)	Distance (m)	Average speed (km/h)
Standard legislative	FTP72-1		505	5 779	41.2
	ECE-15		780	4 052	18.7
INRETS	Short free-flow urban	IUFC	189	999	19.0
	Short rural	IRC	126	1 439	41.1
ARTEMIS	Urban	ART.urban	921	4 472	17.5

A total of 35,941 measurements (combinations of vehicle, cycle and pollutant) were obtained, around a quarter of which related to unregulated pollutants. In total, the database included 1,766 vehicles for regulated pollutants and 102 vehicles for unregulated pollutants. For the regulated pollutants, the numbers of vehicles tested are shown in **Table B7-2**. All the vehicles were selected by the various laboratories involved so that the sample distribution was representative, as far as possible, of the fleet corresponding to each country. There were few data for pre-Euro I diesel cars with an oxidation catalyst. For some of the categories in **Table B7-2**, there were not enough vehicles to give a robust estimate of cold-start emissions, and therefore some categories were merged in ARTEMIS.

Table B7-2: Vehicle sample size by driving cycle (regulated pollutants).

Cycle name	Emission standard	Fuel type	Vehicles
ECE-15	Pre-Euro I, no catalyst	Petrol	288
	Pre-Euro I, catalyst	Petrol	739
	Euro I	Diesel	3
		Petrol	36
	Euro II	Petrol	26
FTP72-1	Pre-Euro I, no catalyst	Diesel	7
	Pre-Euro I, catalyst	Petrol	727
		Diesel	16
	Euro I	Diesel	3
		Petrol	3
	Euro II	Diesel	16
		Petrol	5
	Euro III	Diesel	2
		Petrol	10
IRC	Pre-Euro I, no catalyst	Petrol	17
	Pre-Euro I, catalyst	Petrol	10
	Euro I	Diesel	3
		Petrol	4
	Euro II	Diesel	17
		Petrol	8
	Euro III	Diesel	4
		Petrol	12
IUFC	Pre-Euro I, no catalyst	Petrol	29
	Pre-Euro I, catalyst	Petrol	10
	Euro I	Diesel	3
		Petrol	4
	Euro II	Diesel	29
		Petrol	16
	Euro III	Diesel	4
		Petrol	45
	Euro IV	Petrol	7

B7.3.2 Cold-start excess emission and distance calculation

The ARTEMIS modelling approach was built on the hypothesis that the cold-start excess emission depends on the engine start temperature as the only temperature-related parameter, this being equal to the ambient temperature for a full cold start, or greater than the ambient temperature in the case of a 'warm' start (*i.e.* when the engine temperature is higher than the ambient temperature but lower than the full operational temperature). This hypothesis was necessary due to the lack of data for certain conditions. For example, no data were available for vehicles starting with an engine temperature of 0°C when the ambient temperature was 10°C. Three different approaches to estimating the cold-start distance and the cold-start emission were examined, and these are summarised below.

First method: standard deviation

This method was developed previously at INRETS (Joumard and Serié, 1999) and involves calculating the standard deviation on the measurements working backwards from the end of the cycle, adding one measurement at a time. As long as the emissions are stable (*i.e.* hot), the variation occurs randomly around a mean (the hot emission), and the standard deviation therefore decreases as the number of points considered increases. However, the standard deviation increases rapidly as soon as cold-start part of the cycle is reached, and the cold-start distance therefore equates to the minimum value of the standard deviation. The hot emission is calculated from the values beyond (forward in time) the minimum. The absolute cold-start emission is calculated over the entire cold-start distance, and the cold-start excess emission is calculated by subtracting the hot emission from the absolute cold-start emission.

Second method: linear regression

This method, developed at EMPA (Weilenmann, 2001), considers the continuous cumulative emission from the start of the cycle. A linear regression model is then fitted to the cumulative emission data from the hot part of the cycle alone, and the regression value at zero distance gives the cold-start emission value. The hot/cold limit is initially chosen arbitrarily, and then by plotting two straight lines parallel to the linear regression during the rough hot part. The lines have the same gradient, but the constant of the first line is equal to 95% of the emission, whilst that of the second line is equal to 105% of the emission. The precise cold-start distance is determined from the last point in time when the total emission falls between the two lines. This method can give slightly different results to the first method for d_{cold} and the cold-start emission.

Third method: linear regression and standard deviation (used in ARTEMIS)

A third method was specifically developed for the ARTEMIS project, and combined the two methods described above. The emission per cycle and the standard deviation are initially calculated on the basis of the first method. The cold-start period is also determined approximately according to the first method, when the standard deviation is a minimum. This permits the calculation of the hot emission. The linear regression of the cumulative emission over the hot stabilised period is then used to give the cold-start excess emission at zero distance. The exact cold-start distance is determined as the distance at which the emission falls entirely between two straight lines which are the hot emission plus or minus two standard deviations. The ARTEMIS method is illustrated in **Figure B7-2**. **Table B7-3** shows that, for the same emission data, the three methods give almost the same cold-start excess emission, but not the same cold-start distance.

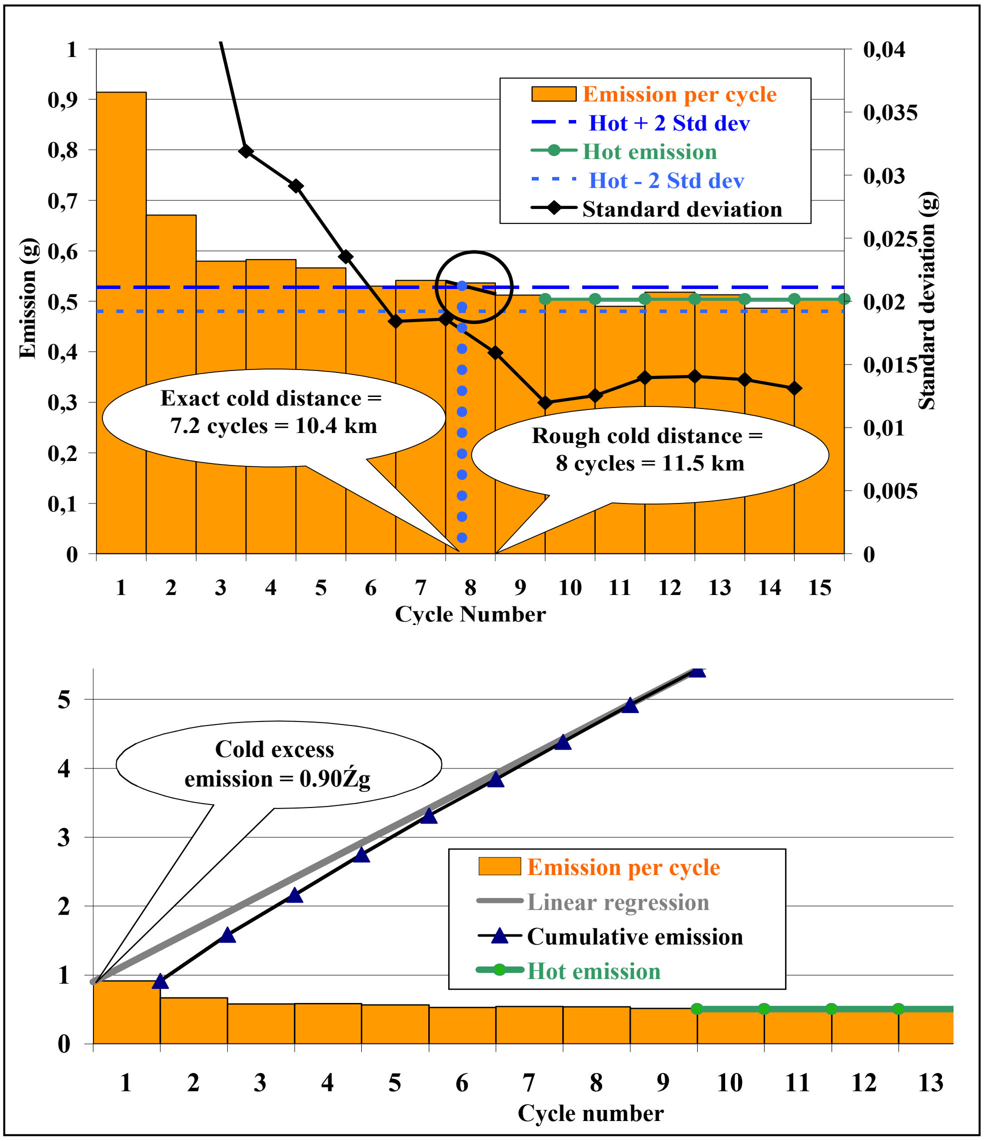

Figure B7-2: ARTEMIS method for calculating the cold-start excess emission. Example of calculation of the approximate and exact cold-start distances (top), and the cold-start excess emission (bottom).

Table B7-3: Comparison of the cold-start distance and the cold-start CO emission (Euro I diesel at 18°C) calculated using the different methods.

Method	Cold-start distance (km)	Cold-start excess emission (g)
Standard deviation	13.5	0.89
Linear regression	10.1	0.89
ARTEMIS	10.4	0.90

The cold-start emission factors for unregulated pollutants were not measured over successive cycles. In order to calculate the excess emission, the cold distance was, for all the unregulated pollutants, taken to be equal to that for THC. The cold-start excess emission was then calculated as the difference between the emission over a cycle beginning under cold-start conditions and the emission over the same cycle beginning under hot-start conditions.

A previous study (Joumard *et al.*, 1995) showed that the ECE-15 cycle did not cover the entire cold-start period. The ECE-15 cycle corresponds to an average speed of 18.7 km/h and a distance of 4,052 m. The excess emission calculated over the ECE-15 cycle corresponded to 80% of the total excess emission over the short, free-flow urban cycle. Consequently, a correction factor was developed for this cycle to transform the measured excess emission into a 'full' excess emission. The correction factor was derived via comparison with measurements recorded using the IUFC cycle (mean speed similar to the ECE-15), which covered the whole cold-start period.

When applying the whole ARTEMIS methodology, the cold-start distance for the four regulated pollutants, two driving cycles (at 19.0 and 41.1 km/h), and a number of cases (vehicle type, ambient temperature) ranged from 2 km to 9 km, with an average of 5.2 km at 20°C.

B7.4 Influence of various parameters

In this Section, the influence of the ambient temperature, the average speed, the distance and the parking duration on excess emissions is described. The aim is to express the excess emission E_{cold} as:

$$E_{cold}(T,V,\delta,t) = \omega_{20°C,\,20\,km/h} \cdot f(T,V) \cdot h(\delta) \cdot g(t) \qquad \text{(Equation B7-2)}$$

Where:

$E_{cold}\ (T,V,\delta,t)$	=	excess emission in grammes per start
T	=	temperature (°C)
V	=	average speed (km/h)
$\delta = d/d_c$	=	dimensionless distance travelled
d	=	distance travelled (km)
d_c	=	cold-start distance (km)
t	=	parking time
$\omega_{20°C,20km/h}$	=	excess emission (g) at 20°C and 20 km/h
$f(T,V) = \omega(T,V)/\ \omega_{20°C,20km/h}$	=	cycle speed and temperature influence (see Section B7.4.1)
$h(\delta)$	=	distance influence (see Section B7.4.2)
$g(t)$	=	parking-time influence (see Section B7.4.3)

B7.4.1 Excess emission as a function of cycle speed and temperature

Following the merging of vehicle categories and the correction for the ECE-15 cycle, a 3-D linear regression model was used to derive the excess emission level $\omega(T,V)$ (in grammes) as a function of average speed V (km/h) and the temperature T (°C). The boundaries of the measurement points for the linear regression calculation were -20°C to +30°C for the ambient temperature, and 18 km/h to 42 km/h for the mean speed. It should be noted that the regression was calculated using only four speeds. Outside the boundaries, the values of the regression must be treated with caution.

B7.4.2 Excess emission as a function of the distance travelled

Initially, the cold-start distance d_{cold} was modelled as a function of vehicle speed V and ambient temperature T. In many cases, d_{cold} was only available for only one temperature (20°C) and two speeds. In such cases, d_{cold} was taken to be only a function of V. In other cases, the temperature dependence of d_{cold} was only available for one speed (19 km/h). Both d_{cold} and the excess emission were therefore expressed as functions of V and T. Again, the boundaries of the linear regression calculation were -20°C to +30°C and 18 km/h to 42 km/h. Consequently, both the excess emission and the distance travelled could be made dimensionless, and the influence of the dimensionless distance (***δ=d/d_cold***) on the dimensionless excess emission could be investigated. This effect is expressed as an exponential function ***h(δ)***. This function for ***h(δ)*** could be influenced by the ambient temperature ***T*** and the average speed ***V***, but in fact the effects of ***V*** and ***T*** are very small. Therefore ***h(δ)*** can be expressed as:

$$h(\delta)=\frac{1-e^{a\cdot\delta}}{1-e^{a}} \qquad \text{with } \delta=\frac{d}{d_c}$$

(Equation B7-3)

where ***a*** is deduced from the data.

For the unregulated pollutants, the emission evolution during the cold-start phase was not measured, and therefore the ***h*** function for unregulated pollutants was taken to be that for THC.

B7.4.3 Excess emission as a function of parking duration

In order to take into account the parking duration, which affects the initial engine temperature, the influence of parking duration on the excess emission needs to be determined. Unfortunately, appropriate data are rare, and only a small number of studies have been reported. A CARB study (Sabate, 1996) looked at the parking time influence on emissions using the FTP cycle. The cold-start period was defined as the first 100 seconds. Hammarström (2002) examined the effects of short parking durations (less than one hour) on excess cold-start exhaust emissions from two petrol non-catalyst cars and two petrol catalyst cars. Starts of 10, 20, 30 and 60 minutes were examined using several repeats of the FTP cycle. It was hypothesised that after the fourth FTP cycle of the warm-up phase each car would have a stabilised emission level, that start effects would be expected mainly from the first FTP cycle, and that a stabilised emission level would be reached before the third FTP cycle. The statistical analysis showed that theses hypotheses were wrong. Schweizer *et al*. (1997) investigated the parking time influence on emissions using a city-centre driving cycle (EMPA T50, distance: 6.51 km, average speed: 28 km/h). As with the FTP cycle, this cycle is too short to enable the full operational vehicle temperature to be reached. The study showed that the excess emission increased rapidly for short parking times and levelled off for parking times longer than one hour. The full cold-start excess emission was reached after 12 hours of parking. In a study conducted by TUG, Hausberger (1997) used a driving cycle which represented driving behaviour in an underground parking lot. Tests were conducted on five petrol catalyst cars (Euro I), three petrol cars without catalyst (pre-Euro I and older) and four diesel cars (Euro I). The parking durations were 0.5, 1, 2, 4 and 16 hours.

The data from all these studies were used to calculate average parking duration effects for each pollutant. The CARB data were not used because of the non-representativeness of European conditions, and the likelihood that the 100-second period did not include the full cold start. The function ***g(t)*** was taken to be equal to one following a parking period of 12 hours.

B7.5 The ARTEMIS cold start models

The general ARTEMIS model for cold-start emissions was a function of ambient temperature, average speed, distance travelled and parking duration. In fact, three different models were developed to calculate cold-start excess emissions using the types of information available to the user. All the proposed models are described for a pollutant and a vehicle type (*i.e.* for a given fuel type and a given emission standard).

B7.5.1 Model 1: excess emission per start

This model gives an excess emission per start (*i.e.* per trip) in grammes for a given car type and pollutant, as a function of the ambient temperature ***T***, the mean speed during the cold period ***V***, the travelled distance ***d***, and the parking time ***t***.

$$E_{cold}(p,T,V,d,t) = \omega_{20°C,\,20\,km/h}(p)\cdot f(p,T,V)\cdot h(T,\delta(p,T,V,d))\cdot g(p,t)$$

(Equation B7-5)

Where:

E_{cold}	=	excess emission for a trip (g)
p	=	atmospheric pollutant
T	=	ambient temperature (°C)
V	=	mean speed during the cold period (km/h)
$\delta(p,T,V,d)$	=	dimensionless distance = $d/d_c\,(p,T,V)$
d	=	distance travelled (km)
$d_c(p,T,V)$	=	cold distance (km) for the pollutant p
$\omega_{20°C,20km/h}(p)$	=	reference excess emission (at 20°C and 20 km/h) for a trip distance longer than the cold

		distance, *i.e.* in any case longer than 15 km (g), for the pollutant ***p***
f(p,T,V)	=	plane function of the speed ***V*** and the temperature ***T***, for the pollutant ***p***
h(p,δ)	=	$\frac{1-e^{a(p)\cdot\delta}}{1-e^{a(p)}}$
a(p)	=	constant coefficient for the pollutant ***p***, corresponding to the shape of the dimensionless excess emission.
g(p,t)	=	% of excess emission at 12 h of parking as a function of the parking time ***t*** for the pollutant ***p***
t	=	parking time (***h***)

The values of $\omega_{20°C,20km/h}(p)$ and ***f(p,T,V)*** are available for each pollutant, regulated or unregulated, in André and Joumard (2005). Values for ***h(p,δ)*** and ***g(p,t)*** are not available for unregulated hydrocarbons (URHC). For these, the functions ***h*** and ***g*** for total hydrocarbons are used.

B7.5.2 Model 2: full model of excess emission from traffic

This model gives an excess emission from a stream of traffic in grammes, as a function of:

- Traffic flow
- Season (winter, intermediate, summer, year)
- Average speed
- Ambient temperature
- Hour of the day

Distributions of the distance travelled according to average speed, ambient temperature and parking time are required. Default values are given, but the user can also define the distributions.

$$E_c(p) = \sum_i \frac{cm(s,v_i)}{100} \cdot \omega_i(p) \cdot \left[\sum_h tf_{i,h} \cdot \frac{p_h}{ptf_{i,h}} \cdot \left(\sum_j \sum_m \sum_n \frac{p_{i,j} \cdot p_{m,j} \cdot p_{n,h}}{10^6 \cdot d_m} \cdot f(p,V_j,T) \cdot h(p,\delta(p,T,V,d)) \cdot g(p,t_n) \right) \right]$$

(Equation B7-6)

Where:

$E_c(p)$	traffic excess emissions with a cold engine for the pollutant ***p*** corresponding to traffic $tf_{i,h}$ ***(g)***
p	atmospheric pollutant
i	vehicle type
$cm(s,v_i)$	% of mileage under cold-start or intermediate temperature conditions for season ***s*** and overall speed v_i of vehicle type ***i***
s	season (winter, summer, intermediate, year)
v_i	overall average speed for the vehicle type ***i*** (km/h)
$\omega_i(p)$	reference excess emission for the vehicle type i and the pollutant ***p*** (g)
h	hour (1 to 24, day)
$tf_{i,h}$	traffic flow for the studied vehicle type ***i*** and the hour ***h*** (km.veh)
p_h	relative cold-start number for the hour h (average=1)
$ptf_{i,h}$	relative traffic for the studied vehicle type ***i*** and the hour ***h*** (average=1)
j	speed class with a cold engine
m	trip length class
n	class of stops (0 – 1/4, 1/4 – 1/2, 1/2 – 3/4, 3/4 - 1, 1 - 2,... , >12h)
$p_{i,j}$	% of the distance travelled at speed *j* with a cold engine, for the overall average speed, and for the studied vehicle type ***i*** (%)
$p_{m,j}$	% of the distance started with a cold engine and distance d_m, for speed V_j with a cold engine (%)
$p_{n,h}$	% of the distance travelled after a stop with a duration of t_n, for the hour ***h*** (%)
d_m	average distance of the trips under cold-start conditions of class ***m*** (km)
$f(p,V_j,T)$	plane function of the speed V_j and the temperature ***T***, for the pollutant ***p***

V_j	average speed with a cold engine corresponding to class j (km/h)
T	ambient temperature (°C)
$h(p,\delta)$	$(1-e^{a(p,T).\delta})/(1-e^{a(p,T)})$
$a(p)$	constant coefficient for a pollutant p
$\delta(p,T,V_j,d)$	dimensionless distance = $d_m/(d_c(P,_{Vj},T)$
$d_c(p,V_j,T)$	cold distance for the pollutant p (km)
$g(p,t_n)$	% of excess emission at 12h of parking as a function of the parking time t_n for the pollutant p
t_n	parking time (h)

Among all these parameters, different types of parameter can be distinguished:

- Some are purely internal and should not be modified by the user: $\omega_i(p)$, $f(p,V_j,T)$, $d_c(p,V_j,T)$, $h(p,\delta)$ and $g(p,t_n)$.
- Some parameters are input parameters: i, s, v_i, h, tf_{ih}, $ptf_{i,h}$ and T.
- Some parameters are internal parameters, but could be modified by the advanced user: $cm(s,v_i)$, p_h, $p_{i,j}$, $p_{m,j}$, $p_{h,n}$, d_m and V_j

Values of $\omega_i(p)$ and $f(p,V_j,T)$ are given for each pollutant p, regulated or unregulated. Values for $h(p,\delta)$ and $g(p,t_n)$ are not available for the unregulated hydrocarbons. Again, for theses components the functions h and g for the total hydrocarbons are used. Tables of the results are provided by André and Joumard (2005).

According to Duboudin and Crozat (2002), the inclusion of average speed in Equation B7-6 is problematic, because of the possible difference between the average speed during the cold-start period and the average speed during the whole trip. A trip with an average speed v_i is subdivided into a cold-start phase and a hot phase. The cold-start phase can have an average speed V_j which is different to the global speed v_i. To calculate the global emission a hot emission, calculated using v_i, is added, and the cold-start excess emission is calculated using V_j:

$$E_{total}(trip) = E_{cold}(V_j) + E_{hot}(v_i) \qquad \text{(Equation B7-7)}$$

If the distance travelled during the cold-start phase d_c corresponds to an average speed V_j which is different to the speed of the whole trip v_i, the travelled distance under hot conditions cannot have an average speed v_i, and the global emission should be calculated using the formula

$$E_{total}(d_c + d_{hot}) = E_{cold}(V_j, d_c) + E_{hot}(V_j, d_c) + E_{hot}(V_{hot}, d_{hot}) \qquad \text{(Equation B7-8)}$$

where V_{hot} is the average speed of the hot distance d_{hot}.

B7.5.3 Model 3: aggregated model of excess unit emission from traffic

Models 1 and 2 are not easy to use. The first model needs to be complemented by a model giving the numbers and characteristics of the starts. The second model is the most comprehensive and accurate, but is especially complex to use, and much of the required information is difficult to obtain. The use of this model could lead to misleading results.

Therefore, a simplified approach was developed, whereby the second model, with all its default values, was executed and the outputs were transformed to give excess cold-start emission factors in mass per unit distance, needing only few open input data. The input variables are season, ambient temperature, average speed and hour of the day. The model is, in fact, a combined table of emission factors for four seasons (winter, summer, intermediate, whole year), eight speed classes (5 to 75 km/h), seven temperature classes (-25°C to 35°C) and 25 periods of the day (24 hours and the whole day). Tables of the results are given for the whole day by André and Joumard (2005), and are available for each of the 24 hours as a MicroSoft Excel spreadsheet.

The third model allows the user to take into account the distribution of the cold starts during the day, but its development required a specific assumption on the relative traffic distribution during the day. However, when applying this model, if the actual traffic distribution is very different from the default distribution, the overall emission calculated during the day can be wrong. In such cases, it is recommend that this model is not used on a hourly basis, but that either the second model is used or Model 3 is used for the whole day - the summation over the day of the hourly cold-start excess emissions will be more accurate, but its distribution between the hours of the day will not be accurate.

In order to illustrate the relative effects of the different parameters, some examples are given for CO_2 below. **Figure B7-3** shows the influence of average speed and vehicle type, **Figure B7-4** the influence of ambient temperature and average speed, **Figure B7-5** the season influence, and **Figure B7-6** the influence of the hour of the day. The influence of all these parameters depends on the pollutant considered. Nevertheless, the ambient temperature, the average speed and the hour of the day are generally the most important factors. The season, for a given ambient temperature, plays a minor role.

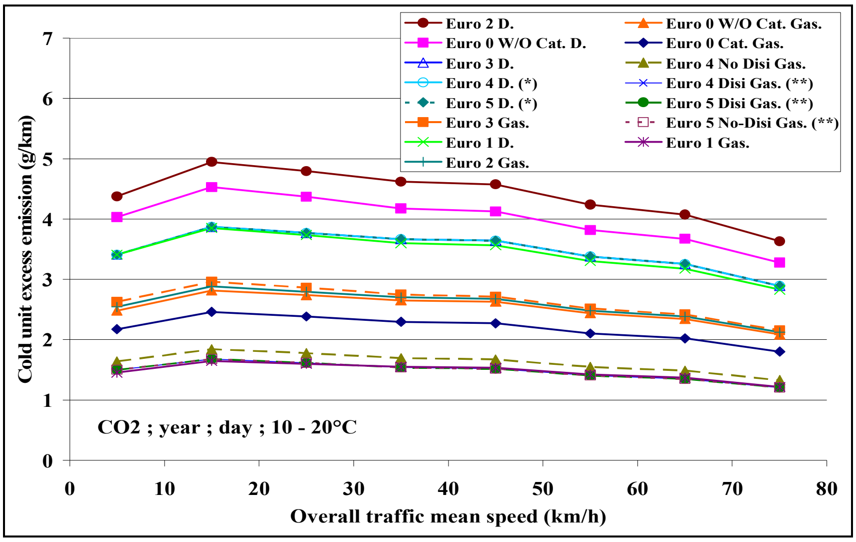

Figure B7-3: CO_2 cold unit excess emission according to average speed and vehicle technology (ambient temperature: 10-20°C, season: year, hour: whole day) (g/km).

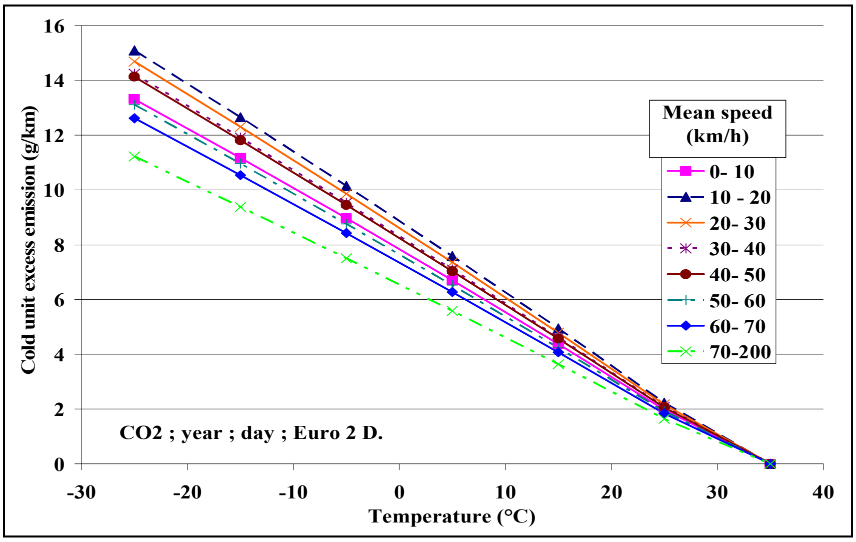

Figure B7-4: CO_2 cold unit excess emission according to ambient temperature and average speed for Euro II petrol cars (season: year, hour: whole day) (g/km).

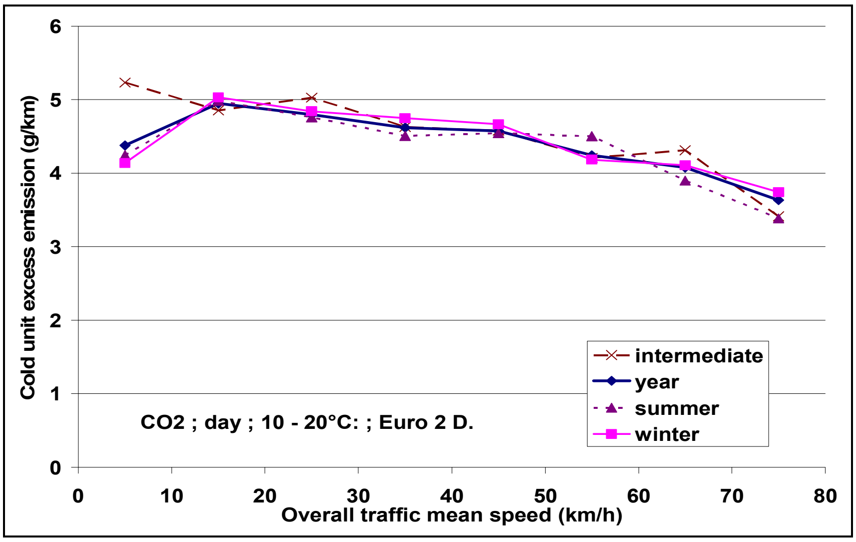

Figure B7-5: CO_2 cold unit excess emission according to season and average speed (ambient temperature: 10-20°C, petrol Euro II) (g/km).

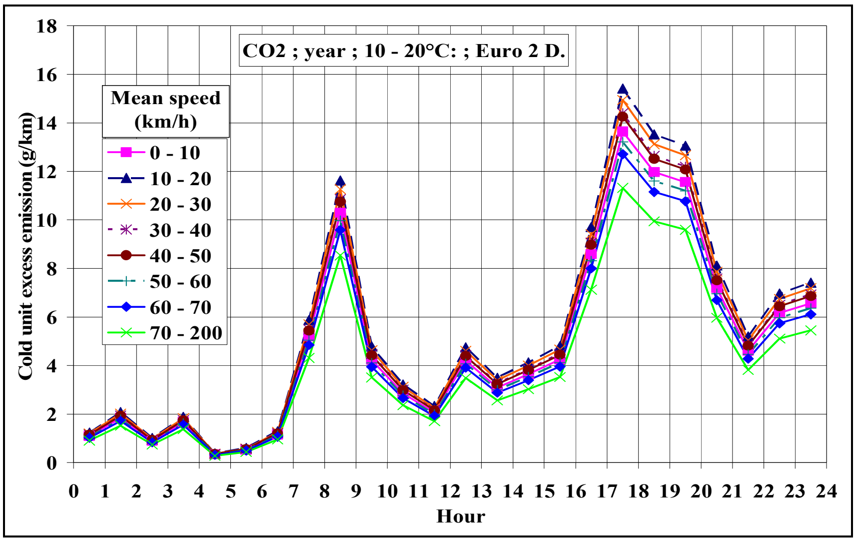

Figure B7-6: CO_2 cold unit excess emission according to hour and average speed (ambient temperature: 10-20°C, petrol Euro II) (g/km).

B7.6 Conclusions

The modelling of excess emissions under cold-start conditions for passenger cars was achieved using data provided by various European research organisations as part of the MEET and ARTEMIS projects. Three models were developed, taking into account average speed, ambient temperature, distance travelled and parking duration, amongst other parameters. The models were based on measurements made over four driving cycles at different ambient temperatures. The average speeds of the cycles ranged from 18.7 km/h to 41.5 km/h, and the temperatures ranged from -20°C to 28°C.

In a first model the cold-start excess emission was expressed in grammes per start for a given pollutant and vehicle technology. The general formula was written in the form of a reference excess emission multiplied by functions depending on average speed, ambient temperature, distance travelled and parking duration. A second model was developed to assess the excess emissions from traffic. The model requires extensive driving behaviour statistics, and is therefore very complex, but it allows the experienced user to modify the input data in order to model very specific situations. A third, simplified model was derived from the second model, and provides a unit excess emission in g/km. It takes into account the average speed, the ambient temperature, the hour of the day and the season.

The three models are available for numerous vehicle technologies (fuel and emission standard) covering the European situation, and for regulated as unregulated pollutants. The models can be applied at different geographic scales - at a macroscopic scale (national inventories) using road traffic indicators and temperature statistics, or at a microscopic scale for vehicles and trips. Where a model user does not have access to the necessary statistics, it is recommended that the most aggregated model (*i.e.* the third model) is used.

All three models are improved versions of the former MEET model, and the third model should replace the existing COPERT III cold-start model.

This study corresponds to the state-of-the-art at the present time. In the future, the models could be improved in the following ways:

- By updating the models using new data when available, either for the most recent passenger cars, light commercial vehicles or heavy-duty vehicles.
- It would be much more precise to have cross-distributions for different speeds and ambient temperatures.
- The amount of supporting data has to be increased, especially for different speeds, lower and higher temperatures, and unregulated pollutants.

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B8 EVAPORATIVE EMISSIONS

B8.1 Background

This Section of Part B describes the data, methods and results from the ARTEMIS investigations into evaporative emissions of volatile organic compounds (VOCs) from petrol-engined vehicles.

B8.1.1 Sources of evaporative emissions

Evaporative losses of VOCs from petrol vehicle fuel systems (tanks, injection systems and fuel lines) occur as a result the diurnal variation in ambient temperature and the temperature changes of the vehicle fuel system which occur during normal driving. Evaporative emissions consist mainly of light hydrocarbons (C_4 to C_6), and a significantly higher proportion of olefins is found in the vapour than in the base fuel (CONCAWE, 1987). Evaporative emissions from diesel-fueled vehicles are considered to be negligible due to the extremely low volatility of diesel fuel.

There are five main mechanisms by which petrol evaporates from vehicles:

(i) *Diurnal losses*. These occur when a vehicle is stationary and the engine is turned off. Diurnal losses are due to the thermal expansion and emission of vapour, mainly from the fuel tank, as a result of changes in ambient temperature during the day. This mechanism is also known as 'tank breathing'.

(ii) *Resting Losses*. These are identified as a separate evaporative source in some of the more recent studies, and result from diffusion, permeation, seepage and minor liquid leaks. If resting losses are not considered as a separate category they are usually included in the hot-soak and diurnal categories, although they can also be considered as background emissions, and independent of diurnal losses. Resting losses do not need an increase in fuel temperature to occur.

(iii) *Hot-soak losses*. These occur when a warmed-up vehicle is stationary and the engine is turned off. In the absence of windblast, more engine heat is dissipated into the fuel system. The increasing temperature causes evaporative emissions.

(iv) *Running losses*. These are defined as emissions which occur whilst a vehicle is being driven. The heat emitted from the engine and the changing windblast result in variable temperatures in the fuel system.

(v) *Refueling losses*. These occur while the tank is being filled and the saturated vapours are displaced and vented into the atmosphere. They are usually attributed to the fuel handling chain and not to the vehicle emissions. Refueling losses are therefore not addressed here.

Evaporative emissions from motor vehicles are dependent upon four major factors:

- Vehicle and fuel system design.
- Ambient temperature and its daily variation.
- Petrol volatility - usually expressed by the empirical fuel parameter known as Reid vapour pressure (RVP).
- Driving conditions (trip length, parking time, *etc.*).

The effects of these factors on evaporative emissions have been the subject of numerous studies. The earliest studies were carried out in the United States in the 1960s (*e.g.* Wade, 1967), but the first European studies were only conducted twenty years later (CONCAWE, 1987, 1988 and 1990). Within the last decade, few measurements of evaporative emission factors have been made in Europe and consequently evaporative emission models have not been updated. Measurements and studies later than mid-2005 have not been considered here, since the work on evaporative emissions within ARTEMIS was finalised in July 2005.

Several species of hydrocarbon are associated with direct health effects, and also contribute, via chemical reactions with NO_x in the presence of sunlight, to the formation of photochemical smog. Evaporative emissions are almost exclusively a summer problem due to their approximately exponential sensitivity to ambient temperature. It is on hot sunny days, when ozone levels are the highest, that evaporative emissions can account for the majority of the total vehicle HC emissions. Concern regarding the control of evaporative emissions has grown over the years as exceedances of the health-based ozone standard have continued to be a problem in many areas.

B8.1.2 Control of evaporative emissions

Evaporative emissions are not easily controlled due to the fact that venting of the vehicle tank system must be provided so it can 'breathe' during temperature changes. In the past, fuel vapours were simply vented into the atmosphere. Nowadays, the control of evaporative emissions can be achieved via the control of fuel properties and by vehicle technology, and these two aspects are discussed briefly below.

Fuel properties

The fuel standard in Europe for vehicles equipped with positive ignition engines is defined in Directive 98/70/EC. This introduced tighter standards on a number of fuel properties affecting emissions. The Directive states that the RVP during the summer period is limited to 60 kPa, with the summer period beginning no later than 1 May and not ending before 30 September. However, 'for Member States with arctic conditions', the summer period shall begin no later than 1 June and not end before 31 August and the RVP is limited to 70 kPa.

Vehicle technology

The early attempts to reduce evaporative emissions were relatively simple mechanical modifications, such as using pressurised fuel tanks with pressure/vacuum relief valves, sealing leaks, venting of the carburettor float-bowl into the air-cleaner and venting of fuel tanks into the crankcase. In the United States, positive crankcase ventilation (PCV) was introduced in 1963. This aimed to recycle the blow-by vapours in the crankcase back into the intake manifold so they could be re-burned. This virtually eliminated crankcase emissions as a source of air pollution. Sealed fuel systems and charcoal canisters appeared in 1971 (Hausberger *et al*., 2005)..

Although there has been an increasing environmental concern with evaporative emissions, much more attention is usually paid to exhaust emissions. This has especially been the case in Europe, where contrary to the US, Japan and Australia, no evaporative emission limits were applied until 1993. Up to this point, numerous improvements in both evaporative control systems and testing standards were already introduced in the US. Consequently, the phase-in of vehicles with so-called 'enhanced' evaporative control systems started in the US in 1996 (Hausberger *et al*., 2005).

Most modern evaporative emission control systems employ an adsorption canister filled with charcoal, which is connected to both the fuel tank and the engine intake manifold. **Figure B8-1** shows a schematic picture of a typical evaporative control system. The charcoal adsorbs any excess fuel vapour produced from the tank. The vapour can be then purged into the intake manifold when the engine is running under certain conditions, so that the VOCs can be burned along with the fuel-air mixture. On modern vehicles canister purge is controlled by a purge valve, which is placed between the charcoal canister and the engine intake manifold and is regulated by engine management (Hausberger *et al*., 2005).

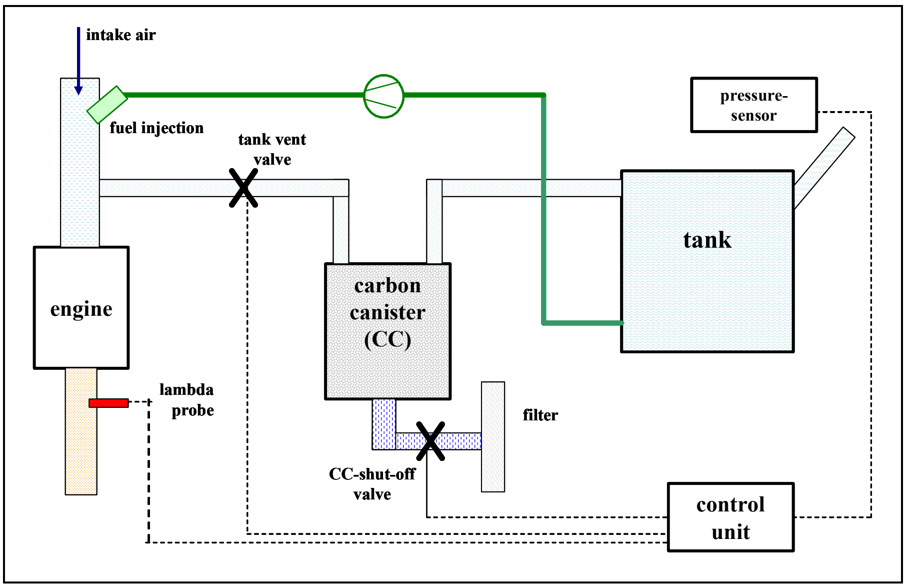

Figure B8-1: Basic components of an evaporative emission control system (Hausberger *et al*., 2005).

In spite of today's rigorous emission controls and petrol regulations, the problem of evaporative emissions still remain – emanating from older uncontrolled vehicles, vehicles with defective evaporative control systems, motorcycles, petrol power tools and a variety of recreational vehicles.

B8.1.3 ARTEMIS objectives

The principal objective in ARTEMIS was to develop a model for estimating evaporative emissions from passenger cars and two-wheel vehicles, and from pre-Euro I to Euro IV. The model was based mainly upon existing information in the literature. A literature review conducted at the beginning of the project and some basic experiments identified the main gaps in the existing data, and the measurement programme was designed accordingly. The objectives of the measurement programme were:

(i) To provide data on evaporative emissions from modern cars, since no data were found in the European literature on their real-world emission behaviour. For example, the existing emission factors for Euro III and Euro IV vehicles were not based on measured data.

(ii) To provide data on evaporative emissions for temperature conditions other than those encountered during type approval, especially for multiple-day parking and high-temperature cycles. Under these conditions the canister may be saturated before the end of the test, leading to steep increases in the evaporative emissions over the cycle.

(iii) To provide data on the behaviour of European vehicles over the USEPA test cycles, in order to develop methods to make use of the extensive test data from the USEPA.

B8.2 Measurement programme

The ARTEMIS measurement programme covered diurnal losses, resting losses and hot-soak losses. Running losses were not measured since an appropriate facility was not available, and these were therefore quantified via a literature review. The following Sections provide an overview on the work, and more detailed information is presented by Hausberger *et al*. (2005). Only three cars and one motorcycle were measured within ARTEMIS, although the model makes use of existing measurements.

B8.2.1 Method

Test facility

All the evaporative emission measurements were carried out in the SHED (Sealed Housing for Evaporative Determination) facility at FH Joanneum GmbH in Graz, Austria (**Figure B8-2**). This SHED was constructed from stainless steel, with a usable test chamber volume of 51 m^3 and temperature range of 18^{o}C to 45^{o}C. Hydrocarbons were measured using a flame ionisation detector.

Figure B8-2: SHED facility at FH Joanneum GmbH Graz, Austria.

Test programme and procedure

The test programme was designed so that evaporative diurnal losses could be measured over different temperature cycles (*i.e.* different minimum diurnal temperatures and diurnal temperature variations). Both the European and US test procedures were used in order to be able to compare the different results and to assess if the measurements from USEPA were representative of European conditions. Finally, the models were validated with the measured data. In total, three temperature cycles were chosen:

(i) The European 20-35°C cycle, which was used in the enhanced (Euro III/IV) evaporative testing procedure (1999/102/EC),

(ii) The standard USEPA 72-96 °F (22.2-35.6°C) temperature cycle, and

(iii) An additional USEPA 82-106 °F (27.8-41.1°C) cycle.

Both USEPA diurnal temperature cycles were repeated twice, resulting in 48-hours tests. These temperature cycles are shown in **Figure B8-3**.

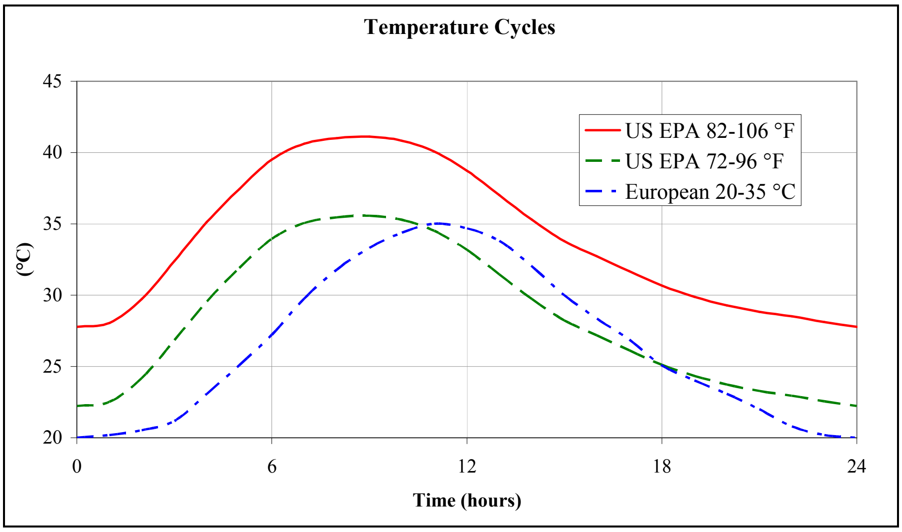

Figure B8-3: The three temperature cycles used in the ARTEMIS diurnal evaporative tests.

Hot-soak emissions were not measured at different ambient temperatures - they were simulated by warming-up the vehicle with a specified driving cycle and then allowing it to soak for one hour at the legally prescribed SHED temperatures. During the European testing procedure, the hot-soak SHED temperature was kept constant at 27°C. The hot-soak measurements according to the USEPA testing procedure were performed without regulating the SHED temperature. The two testing procedures (European and US federal) differ not only in temperature cycles, but also in preconditioning driving cycles and other details. The diurnal test results are not only affected by the different temperature cycles, but also by the differences in the testing procedures, *i.e.* canister preconditioning (loading and purging) and preconditioning cycles driven prior to hot-soak and diurnal measurements. In order to improve the repeatability of the evaporative measurements, a special preconditioning procedure has been established (Tripolt *et al.*, 2004). Before the first measurement on each vehicle, the carbon canister was removed and subjected to multiple purging and loading cycles in a butane loading station. Loading was performed with a butane/nitrogen mixture (50 %vol butane and 50 %vol nitrogen) with a loading value of 40 g of butane per hour, and purging was achieved with laboratory air at a flow rate of 25 litres per minute. In total, three purging and loading cycles were carried out. Then the carbon canister was refitted in the car, and the legally prescribed preconditioning routine was initiated.

Test vehicles

The cars for the SHED tests were selected to cover different categories from small cars to SUVs, and carbon canisters of different volume (**Table B8-1**). The vehicles tested were obtained from car dealers, and were in a good service condition with rather low mileage. All the cars were Euro III certified. Thus, the vehicles represented 'enhanced evaporative controlled vehicles' without failures.

Table B8-1: Description of test vehicles.

Vehicle type	Make and model	Certification level	Year of first registration	Odometer (km)	Rated power (kW)	Carbon canister volume (l)	Tank volume (l)
Passenger car	Mitsubishi Colt 1.3	Euro III	2004	7,375	70	0.95	47
Passenger car	Opel Vectra 1.8	Euro III	2003	21,346	90	1.9	61
Passenger car	Jeep Grand Cherokee	Euro III	2003	20,279	140	2.4	95
Motorcycle	Honda Hornet 900	Euro II	2003	3,243	78	-	19

Test fuel

A common test fuel was used for all the tests - the CEC legislative fuel RF-08-A-85 (EU). The testing of different fuels was not foreseen in the project due to budget restrictions. Fuel effects were therefore determined via a review of the literature.

B8.2.2 Results

Table B8-2 summarises the results of the measurements. The preconditioning and the prescribed temperature curves are different in the EU and US testing procedure. The purge volumes during preconditioning driving cycles during the European testing procedure were significantly higher than the purge volumes during the US testing procedure. Therefore, it could be assumed that the canister load prior to the hot-soak and diurnal test was also higher during the US tests than during the European tests. However, it was impossible to determine how much the test results were affected by the canister pre-loads.

Another factor that could have affected the diurnal test results was the vehicle temperature (engine, lines and tank) prior to the diurnal test (*i.e.* before the vehicle was placed in the SHED). Although the prescribed conditions (*i.e.* ±2°C of the SHED starting temperature) were always met, it was observed that the temperature of the chamber, where the vehicles were parked prior to the diurnal tests in the SHED, was generally at the upper limit (*i.e.* 22°C) in the European tests. Therefore, during the European tests the vehicles were usually slightly warmer (1-2°C) than the SHED starting temperature, whilst during the US tests the vehicles were generally at the SHED starting temperature. Thus, in the case of the European test the vehicles probably cooled down during the starting phase of the test, which may have reduced the evaporation during this period[35]. These two factors were probably the predominant reasons for the significantly higher diurnal test results (1.43 g/day compared with 0.96 g/day average diurnal emissions - *i.e.*, 49% higher) during the US tests than during the European tests.

Table B8-2: Summary of test data for all vehicles.

Vehicle		Mitsubishi Colt 1.3	Opel Vectra 1.8	Jeep Grand Cherokee	*Mean (cars)*	Honda Hornet 900 (Motorcycle)
EU SHED 2000 evaporative testing procedure, temperature cycle: 20-35 °C	Hot-soak (g/test)	0.10	0.13	0.10	*0.11*	6.46
	Diurnal (g/day)	1.40	1.01	0.46	*0.96*	8.13
US enhanced evaporative testing procedure, temperature cycle: 72-96°F (22.2-35.6 °C)	Hot-soak (g/test)	0.08	0.18	0.08	*0.11*	2.55
	1st Diurnal (g/day)	2.17	1.63	0.49	*1.43*	7.84
	2nd Diurnal (g/day)	4.88	2.26	0.45	*2.53*	7.50
US enhanced evaporative testing procedure, temperature cycle:82-106°F (27.8-41.1 °C)	Hot-soak (g/test)	0.09	0.18	0.08	*0.12*	2.03
	1st Diurnal (g/day)	>8.7*	2.05	0.62	*3.79*	12.44
	2nd Diurnal (g/day)	--	2.51	0.90	-	11.48

*Measurement range was exceeded close to the end of 1st day diurnal test.

Additional SHED test results from TÜV-Nord for one moped and nine motorcycles were made available for the ARTEMIS project (Braun and Gersdorf, 2000). The motorcycles examined by TÜV-Nord were preconditioned according to the EU SHED 2000 regulation. Emissions from the motorcycle tested in ARTEMIS (Honda Hornet) were within the ranges obtained by TÜV Nord when the FTP cycle was used for preconditioning. The use of the WMTC for preconditioning in the ARTEMIS measurement programme resulted in more than double the hot-soak emissions recorded using the FTP, probably due to the much higher engine power demand of the WMTC leading to a hotter engine at the end of the preconditioning. As expected, the ARTEMIS diurnal test over the high temperature cycle (82-106 °F) resulted in higher diurnal losses than the standard tests.

B8.3 Comparisons between ARTEMIS measurements and previous models

B8.3.1 Diurnal losses

Evaporative emissions over the test cycles were calculated using the CORINAIR (COPERT), RWTÜV and MOBILE 6 models. MOBILE 6 is the standard inventory model from USEPA. The MOBILE 6 values represent the sum of both diurnal and 24-hour resting losses for the vehicle category '1999-2003 pass both' (*i.e.* vehicles with an enhanced evaporative system). The RWTÜV values are calculated using the coefficients for summer petrol since the fuel quality is not a direct input parameter for this model. The comparison of the calculated values to the measured data is shown in **Figure B8-4**.

[35] The temperature change in the European diurnal test cycles was therefore smaller in the fuel system than in the test chamber, which has to be taken into consideration when comparing the measurement results with the model prediction.

There were significant discrepancies between the measured and calculated values. The MOBILE 6 results, even for the cleanest vehicle category (not counting the 2007+ Tier-2 category), were generally much higher than the CORINAIR and RWTÜV estimates and the measured data. Whilst the CORINAIR and RWTÜV values were closer to the measured data at the standard temperature cycles, they clearly underestimated the measured diurnal losses over the US high-temperature cycle, (*i.e.* 82-106°F)[36]. Over this high-temperature cycle, MOBILE 6 still overestimated, but it was closer to the measured value than the other two models. It should be noted that the estimates for vehicles with an enhanced evaporative system were not based on tests on actual in-use vehicles for any of the models reviewed. Thus, the comparison did not allow for the selection of a 'best-fit' model, but it showed that none of the models could reproduce the measurements for Euro III vehicles.

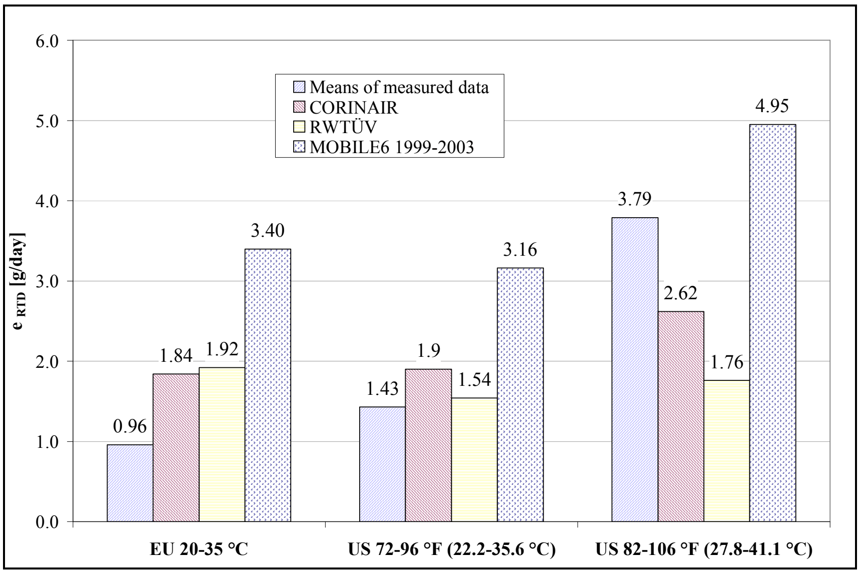

Figure B8-4: Comparison of measured diurnal losses to the calculated diurnal losses according to the CORINAIR, RWTÜV and MOBILE6 (stratum 1999-2003) models for three different temperature cycles.

The RWTÜV model did not reflect the measured trend of increasing diurnal losses following an increase in the test temperature. MOBILE 6 and CORINAIR show an increasing trend that is lower than the one measured.

The much lower diurnal losses measured over the standard European temperature cycle, as opposed to the standard US cycle, were a result of the differences in the test procedures. It is not known which of the cycles is the closer to real-world conditions.

B8.3.2 Hot-soak emissions

Similar model comparisons were also made for hot-soak emissions and two-wheel vehicles (Hausberger *et al*., 2005). Both the COPERT model and the MOBILE 6 model reflected the measured data with a similar accuracy. For Euro II and older cars, MOBILE 6 is based on a much larger number of vehicles and tests. In addition, the MOBILE 6 modelling approach includes additional parameters which are important for estimating evaporative emissions. Therefore, it was decided to adapt the MOBILE 6 model to the actual measurement results. The MOBILE 6 approach was also simplified to make it suitable for the available data in Europe and for the European fleet structure. The adapted model is described in the following Section. It is assumed that the new model is more accurate than the existing ones. However, the available data from SHED tests were too limited to expect reliable emission factors.

B8.4 ARTEMIS evaporative emissions model

The existing European models, such as CORINAIR or RWTÜV, are based on small and outdated experimental data sets and have other weaknesses such as insufficient vehicle stratification (*i.e.* they do not capture the significant improvements in evaporative emission systems beginning with Euro III, when enhanced evaporative systems and OBD were introduced). Another important deficiency of the existing European evaporative models is that they are based on tests on vehicles which were less than three years old. Therefore, the models do not account for a potential increase in evaporative emissions with vehicle age, high-emitters, and vehicles with malfunctioning evaporative systems. As some recent USEPA studies have shown, a few vehicles can account for a large portion of the in-use emissions.

[36] The average of the three cars measured did not necessarily reflect the real fleet average in Europe, since the sample was too small. However, in the absence of any broader database, the measured values are treated as reference values for Euro III.

The USEPA MOBILE6 evaporative model is based on comprehensive test results on in-use vehicles, and does not have the aforementioned deficiencies. On the other hand, it is based on the US in-use vehicle fleet experimental data. Since the measurement programme performed within ARTEMIS gave similar results for European Euro III/IV vehicles over the FTP test as obtained by the EPA with enhanced US cars, this shortcoming does not seem to be problematic. Due to the different measurement protocols, and especially the shorter duration of the European diurnal test compared with the FTP, it was not clear whether manufacturers use different carbon canisters and control strategies for European and US vehicle models. If such a strategy existed, the measured evaporative emissions of the European cars should have been quite high on the second day of the diurnal tests, especially at the high temperature cycles because of a more limited storage capacity of the carbon canister compared with the US cars. Such behaviour was only observed for one of the cars tested. From this result, it was assumed that USEPA data could be considered as being representative of European vehicles (at least for 24-hour diurnal emissions), if the corresponding vehicle categories are selected from the MOBILE 6 model (controlled carbon canisters were introduced in the US much earlier than in Europe).

The following Sections describe the formulae used in ARTEMIS to simulate evaporative emissions. The sources of the formulae are both the USEPA MOBILE 6 and the CORINAIR model, depending on the source of evaporation (diurnals, hot-soak, *etc*.). Some of the parameters of the formulae were adapted to the results of the measurement programme, especially for the Euro III/IV diurnal emissions. The ARTEMIS evaporative emission model covers emissions from the vehicle categories listed in **Table B8-3**.

Table B8-3: Vehicle categories included in ARTEMIS model for evaporative emissions.

Vehicle category	Emission legislation	Source of data
Passenger cars	Pre-Euro I	Literature
Passenger cars	Euro I and Euro II	Literature
Passenger cars	Euro III and Euro IV	ARTEMIS measurements and literature
Passenger cars	Euro I to Euro IV with failures in the evaporation control system	Literature
Motorcycles, >50cc		ARTEMIS measurements and literature
Mopeds, <50 cc		Literature

A formula is given to determine the proportion of vehicles with failures, derived from the in-use tests by the USEPA. Gross liquid leakages, included in MOBILE 6, are not taken into consideration here. Such vehicles may also be on the road in Europe, but including them into the model based on the USEPA results would further increase the evaporative emission factors for the vehicle fleet. Thus, investigations on the conditions of the fuel systems of older European cars needs to be performed in the future if more accurate emission factors are to be obtained.

Data for light goods vehicles (<3,500 kg maximum gross vehicle weight) are not available, and therefore the formulae for passenger cars are used.

The evaporative emission model includes the following sources:

- Real time diurnal losses (sum of diurnal losses and resting losses)
- Hot-soak emissions
- Running losses

The units and symbols given in **Table B8-4** are used in all the subsequent formulae of the model.

Table B8-4: Units used in the equations for the ARTEMIS evaporative emission model.

RVP	[kPa]	Reid vapour pressure
t_a	[°C]	Ambient temperature
t_{min}	[°C]	Minimum temperature of the day
t_{max}	[°C]	Maximum temperature of the day
VP	[kPa]	Vapour pressure at the actual temperature
VP_{mean}	[kPa]	Mean vapour pressure of the day
ΔVP	[kPa]	Difference between highest and lowest vapour pressure within the day
T_{abs}	[K]	Ambient temperature

B8.4.1 Real-time diurnal emissions

In ARTEMIS real-time diurnal (RTD) emissions are defined as a separate category. RTD emissions are a combination of diurnal and resting emissions

Diurnal emissions

For diurnal emissions, formulae from MOBILE 6 (adjusted to SI units) are used. The vapour pressure (VP) of the fuel is calculated as a function of the RVP and temperature. A vapour pressure product term ($VP_{mean} \cdot \Delta VP$) is then determined. This is the product of average vapour pressure during the temperature cycle and the vapour pressure difference over the cycle.

The vapour pressure (VP) can be calculated according to Clausius Clapeyron equation from the RVP:

$$VP = RVP \times e^{A \times \left(\frac{1}{T_{abs}} - \frac{1}{310.9} \right)} \quad \text{[kPa]} \qquad \text{(Equation B8-1)}$$

where:

$$A = -3565.2707 + 10.23 \times RVP$$

If VP_{mean} is the average vapour pressure over the temperature cycle:

$$VP_{mean} = \frac{VP_{T\,max} + VP_{T\,min}}{2} \quad \text{[kPa]} \qquad \text{(Equation B8-2)}$$

ΔVP (difference between VP at highest and lowest ambient temperature in the cycle) is:

$$\Delta VP = VP_{T\,max} - VP_{T\,min} \quad \text{[kPa]} \qquad \text{(Equation B8-3)}$$

$(VP_{mean} \times \Delta VP)$ is called the VP product term according to the nomenclature in MOBILE 6.

From the ***VP*** product term the diurnal emission model was simply derived by plotting the measured evaporative emissions over the corresponding VP product term ($VP_{mean} \cdot \Delta VP$) of the test cycle/test fuel combination. Then a least square approximation is established. **Figure B8-5** shows as example the model for Euro III cars in the ARTEMIS project gained from the three vehicles measured at FH-Joanneum and the average of ten ETP-like vehicles measured at the USEPA.

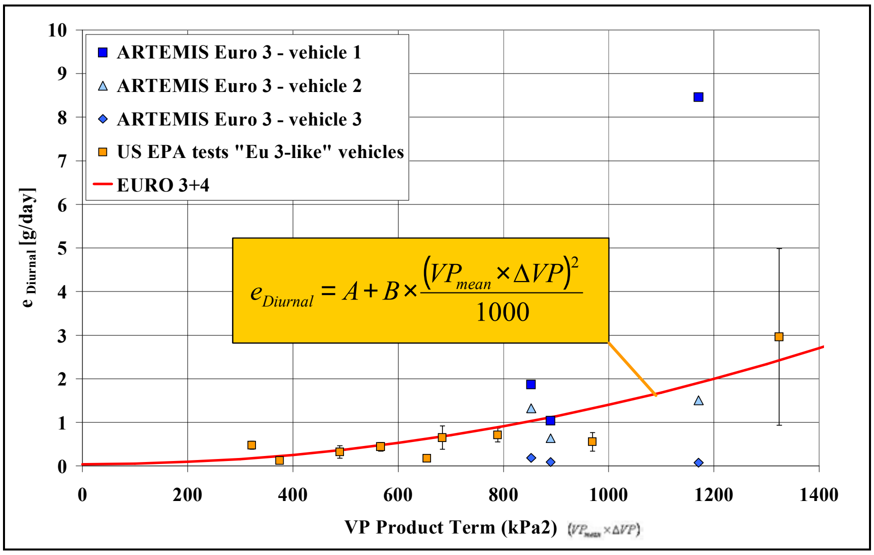

Figure B8-5: ARTEMIS model results for Euro III Euro IV and single measurements for the diurnal losses of Euro III and Euro IV cars and EPA results for 10 enhanced vehicles with the standard deviation.

The high diurnal emission of vehicle 1 (>8 g/day) arose from saturation of the charcoal filter. It cannot be judged from the three cars measured if such high emissions may be found at the same rate in the European car fleet as in the test procedure (1 of 3 cars). More cars would have to be tested to get a representative number (at least the share of cars with small charcoal canister volumes would have to be known to make a better estimation). A high influence in real-world driving may result from the cycle driven before the vehicle is parked since this influences the purging of the charcoal canister and thus is relevant when the canister is saturated. However, no data on this dependency is available at the moment. Thus this parameter is not included in the model.

The data sources and the parameters for the formulae for the different vehicle categories are described below.

Passenger cars

For pre-Euro I and 'Euro I-IV failure' vehicles, the parameters from MOBILE 6 for the model year range 1986-1995 with 'fail pressure' were used for the ARTEMIS model[37]. For Euro I and II vehicles, the model year range 1986-1995 with 'pass both' was used. The parameters ***A*** and ***B*** for Euro III and IV vehicles were adapted according to the ARTEMIS measurement results (**Table B8-5**), since the MOBILE 6 formula for enhanced vehicles is not based on tests but is simply assumed to reduce emissions by 50% compared with the previous models. The measurements performed in ARTEMIS showed lower emission levels for these cars.

$$e_{Diurnal} = A + B \times \frac{(VP_{mean} \times \Delta VP)^2}{1000} \text{ [g/day]} \qquad \text{(Equation B8-4)}$$

Table B8-5: Parameters for calculating diurnal emissions of cars

Vehicle category	*A*	*B*
Pre-Euro I and 'Euro I-IV failure'	0.478	0.015
Euro I and Euro II	0.388	0.005
Euro III and Euro IV	0.037	0.00136

Motorcycles and Mopeds

The diurnal and resting emissions for Motorcycles and Mopeds are calculated according to the same methodology suggested for pre-Euro I passenger cars (since these do not have evaporative emission-control systems), but are adjusted in accordance with the fuel tank volume.

Diurnal emissions for motorcycles (>50 cc):

$$e_{Diurnal} = 0.5 \times e_{Diurnal,\ passenger\ car\ pre-Euro\ I} \text{ [g/day]} \qquad \text{(Equation B8-5)}$$

Diurnal emissions for mopeds (>50 cc):

$$e_{Diurnal} = 0.2 \times e_{diurnal,\ passenger\ car\ pre-Euro\ I} \text{ [g/day]} \qquad \text{(Equation B8-6)}$$

Resting emissions

Resting emissions for cars are calculated using the following equation, and using the coefficients in **Table B8-6**. The allocation between vehicle categories in MOBILE 6 and ARTEMIS is similar to that for the allocation of diurnal emissions.

$$e_{resting} = K \times [A + 0.0051 \times t_{min}] \times 24 \text{ (if results are below zero, } e_{Resting} = 0\text{)} \qquad \text{(Equation B8-7)}$$

[37] The limited number of European vehicles tested did not allow many different vehicle categories to be accurately defined. Thus, several vehicle categories from MOBILE 6 were merged for the ARTEMIS approach.

Table B8-6: Parameters for calculating resting emissions from cars.

Vehicle category	*K*	*A*
Pre-Euro I and 'Euro I-IV failure'	1	-0.019
Euro I and Euro II	1	-0.051
Euro III and Euro IV	0.25	-0.051

The resting emissions for motorcycles (>50 cc) and Mopeds (<50cc) are also based on cars and adjusted in the same way as for Diurnal emissions.

$$e_{resting} = 0.5 \times e_{resting\ ,\ passenger\ \ car\ \ pre-Euro\ \ I} \quad \text{[g/day]} \qquad \text{(Equation B8-8)}$$

$$e_{resting} = 0.2 \times e_{resting\ ,\ passenger\ \ car\ \ pre-Euro\ \ I} \quad \text{[g/day]} \qquad \text{(Equation B8-9)}$$

B8.4.2 Hot-soak emissions

The MOBILE 6 equations are taken as the basis for the suggested formulae, since they are also based on a large database and also include older vehicles with failures in their evaporative emission-control systems.

Pre-Euro I and 'Euro I-IV with failure' vehicles

For pre-Euro I and 'Euro I-IV with failure' vehicles, the MOBILE 6 formula for cars with fuel injection and 'fail pressure' is used. A separate equation for Pre-Euro I cars with a carburettor is not used due to the small differences in the emission level and the high uncertainty in the relative proportions of pre-Euro I vehicles with a carburettor or fuel injection in the fleet. The parameters ***A***, ***B***, and ***C*** were adapted from MOBILE 6 to be compatible with SI units (see **Table B8-7**).

$$e_{HS\ \mathrm{Pr}\ e\ EURO\ /\ EURO\ \ I-IV\ \ Failure} = 0.88 \times e^{\left[A\times\left(RVP-62\right)+B\times t_a+C\right]} \quad \text{[g/test]} \qquad \text{(Equation B8-10)}$$

Table B8-7: Parameters for the hot-soak Pre Euro and for Euro I-IV with failures.

Vehicle category	*A*	*B*	*C*
Pre-Euro I and 'Euro I-IV failure'	0.06	0.0926	-0.8

Euro I and II cars

For 'Euro I and II' vehicles, the MOBILE 6 formula for cars with port fuel injection without failure is used. The parameters ***A***, ***B***, and ***C*** were again adapted from MOBILE 6 to be compatible with SI units (**Table B8-8**).

$$e_{HS\ E1+2} = \frac{\left(A + B \times RVP\right)\times\left(t_a + C\right)}{D} \quad \text{[g/test]} \qquad \text{(Equation B8-11)}$$

Table B8-8: Parameters for hot-soak emissions of Euro I and Euro II cars.

Vehicle category	*A*	*B*	*C*	*D*
Euro I-IV	-0.098	0.12	17.8	740

Euro III and IV cars

According to the ARTEMIS test results, the enhanced controlled cars had approximately 75% lower hot-soak emissions than the EPA model for enhanced cars (*i.e.* Euro I and Euro II cars).

$$e_{HS\ E3+4} = 0.25 \times e_{HS\ \ E1+2} \qquad \text{(Equation B8-12)}$$

Since a hot-soak test represents the evaporative emissions during a cool down from a fully warmed-up vehicle, this is assumed to be equivalent to 'grammes per trip' in the NAEI.

Motorcycles (>50cc)

Constant values are used in ARTEMIS for hot-soak emissions from motorcycles (Hausberger *et al*., 2005). The values, which relate to urban and rural/motorway driving, are given in **Table B8-9**. The value for urban driving was derived from tests over the New European driving cycle (NEDC) preconditioning, and the value for rural and motorway from tests over the WMTC preconditioning. It is assumed that outside cities the average driver uses an engine load in the range of the WMTC (or higher). This results in quite high engine temperatures after shut-off, and correspondingly high increases in the temperature of the fuel tank, which is usually located above the engine. Due to the higher engine temperature after shut-off, the hot-soak emissions are approximately 2.6 times higher after the WMTC than after the NEDC. Hence, the difference in the evaporative emission factors for motorcycles in **Table B8-9**.

Table B8-9: Hot-soak emissions motorcycles>50 cc [g/test].

Vehicle category	Urban	Rural and motorway
e_{HS} > 50ccm	2.5	6.4

Mopeds (<50cc)

As for motorcycles, a constant value is used in ARTEMIS. Since engine loads should be similar during urban and rural driving, one constant factor is used:

$$e_{HS\ M<50cc} = 0.6 \quad \text{[g/test]} \qquad \text{(Equation B8-13)}$$

B8.4.3 Running losses

Cars

For running emissions, the equations from COPERT were used as a basis for the ARTEMIS model. Since the literature review indicated that urban evaporative emissions are much higher in terms of g/km than rural or motorway emissions, additional parameters ***A***, ***B***, and ***C*** are introduced into the formula[38] according to the road category (Hausberger *et al*., 2005). These parameters were derived from the results of EPA studies in which the running emissions are given for three different cycles of 11.5 km/h, 31.5 km/h and 77 km/h. The parameters ***A***, ***B***, and ***C*** were calculated from these experimental data by multiple regression analysis, and are listed i**n Table B8-10**.

$$e_{Running} = A \times 0.136 \times e^{(-5.967 + B \times 0.04259 \times RVP + C \times 0.1773 \times t_a)} \ \text{[g/km]} \qquad \text{(Equation B8-14)}$$

Table B8-10: Parameters for running emissions.

Vehicle category and road type		***A***	***B***	***C***
Pre Euro/	Urban	11	1.2	0.72
Euro I- IV failure	Rural	10	0.98	0.67
	Motorway	4.5	0.95	0.67
Euro I-IV	Urban	1	1.1	0.79
	Rural	0.5	0.95	0.71
	Motorway	0.1	0.8	0.67

Motorcycles and Mopeds

No measurements on running emissions from mopeds and motorcycles were identified during the ARTEMIS project.

B8.4.4 Failure of evaporative emission-control systems

[38] Basing the running emissions on g/h does not eliminate the differences between cycles, therefore units of g/km was used.

The share of Euro I to Euro IV cars with failures in the control system in ARTEMIS (R_{FV}) is calculated according to the results of the USEPA 'fail pressure' data from in-use tests in the United States. The rate of failure is assumed to be lower for Euro III and IV due to the introduction of on-board diagnostics and the durability requirements of the emission-control systems. No data exist which permit the assessment of the situation in Europe. However, it is assumed that it is preferable to use the US data on failures rather than to assume that European cars do not have any failures at all in their fuel systems.

Euro I and II:
$$R_{FV\ EURO\ I\ and\ II} = \frac{0.6045}{1 + 17.333 \times e^{\left[-0.01362 \times (Age)^2\right]}} \quad \text{(Equation B8-15)}$$

Euro III and IV:
$$R_{FV\ EURO\ III\ and\ IV} = \frac{0.6045}{1 + 17.333 \times e^{\left[-0.01362 \times \left(\frac{Age}{2}\right)^2\right]}} \quad \text{(Equation B8-16)}$$

Where the ***Age*** is stated in years.

B8.5 Results and Discussion

In the following paragraphs the ARTEMIS model is compared with the CORINAIR and RWTÜV models for single cars and for a summer day. In the simulation two stops with hot-soaks per day and a total of 35 km driven per day were assumed (1/3 urban, 1/3 road, 1/3 motorway). **Figure B8-6** shows the total daily emission predicted using the models and the aforementioned conditions. The emissions for 'ARTEMIS including failures' are calculated for an average vehicle age of 9 years for Euro I and Euro II, and an age of 2 years for Euro III and Euro IV. This gives failure rates of 9% for Euro I and Euro II, and of 3.3% for Euro III and Euro IV. For comparison, the results for zero per cent cars with failures in the fleet are also shown ('ARTEMIS no failures'). Evaporative emissions increased by 35% for Euro I and II, and 37% for Euro III and IV, according to the failure rates assumed. For pre-Euro I cars, the failure rate has no influence, since pre-Euro I and 'cars with failures in the fuel system' have the same emission factors in the ARTEMIS model.

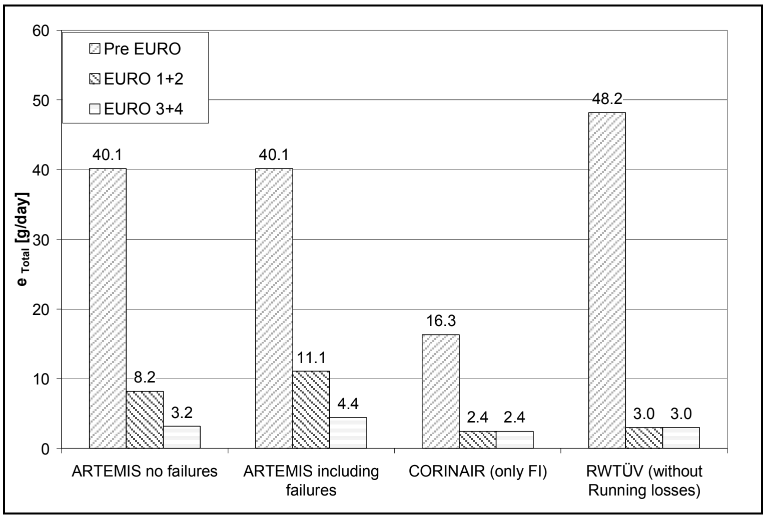

Figure B8-6: Results of total daily evaporative emissions according to the models from ARTEMIS, CORINAIR and RWTÜV for a summer day (t_{min} = 20°C, t_{max} = 35°C; fuel RVP = 60kPa).

For Euro III and IV, all the models gave similar results where only new cars were considered. When cars with failures in the fuel system were included, the ARTEMIS model gave the highest emission value. For Euro I and Euro II, ARTEMIS gave much higher evaporative emissions than either CORINAIR (approx. -80%) or RWTÜV (approx. -70%). It should be noted that none of the models are based on measurements for European Euro I and Euro II cars over real-world diurnal cycles. Since the ARTEMIS data are based upon extensive measurements from the USEPA on vehicles with comparable equipment to European Euro I and II vehicles, it is assumed that ARTEMIS model is more realistic. However, the large differences between the model predictions suggest that if more reliable results are needed, then measurements on this vehicle category have to be performed. For pre-Euro I vehicles, the RWTÜV and ARTEMIS models gave rather similar results, whilst the CORINAIR model gave approximately 60% lower emissions than ARTEMIS.

Figure B8-7 shows the results for colder weather conditions, such as a spring day in Central Europe. Again, the results for Euro III and Euro IV vehicles are similar in CORINAIR and ARTEMIS. Including the failure rate of 3.3% in ARTEMIS results in higher emissions. The RWTÜV model results in the highest emission values for Euro III and Euro IV when using the winter quality term for the fuel. For Euro I and II, RWTÜV and ARTEMIS give nearly the same results, as long as no failure rates are taken into consideration. With failure rates in the fuel system, ARTEMIS gives 50% higher emissions for Euro I and II than without. CORINAIR gives 70% less emissions for Euro I and II than ARTEMIS. The values for pre-Euro I on a spring day also differ a lot. RWTÜV is approx. 150% higher than ARTEMIS, and CORINAIR is nearly 60% lower than ARTEMIS.

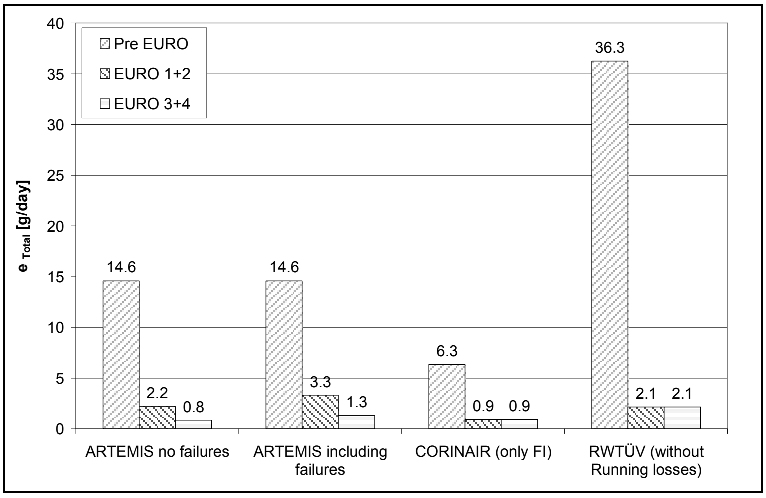

Figure B8-7: Results of total daily evaporative emissions according to the models from ARTEMIS, CORINAIR and RWTÜV for a spring day (tmin=5°C, tmax=15°C; fuel RVP =80kPa).

The existing models for the simulation of evaporative emissions for the European car fleet differ significantly. When applying the new ARTEMIS model, emissions are clearly higher than the results according to CORINAIR, especially under hot-weather conditions. Compared with the RWTÜV model, ARTEMIS sometimes gives higher values and sometimes lower values, depending on the fuel quality and the vehicle category. Since CORINAIR and RWTÜV do not include emissions measured within the last decade, and ARTEMIS is only based on measurements on three new European cars, it is obvious that the database is much too small to establish a really reliable model. Since the measurements performed suggest that the tests done by the USEPA can also be seen as representative for Europe, the ARTEMIS model, based on many of the EPA tests, should be more realistic than the old European models.

B8.6 Conclusions and recommendations

Evaporative emissions mainly occur as a result of temperature changes in the fuel systems of petrol-engined vehicles, which occur due to the daily variation in ambient temperature and during normal driving. Evaporative emissions from diesel-fueled vehicles are negligible due to the extremely low volatility of diesel fuel. In the ARTEMIS model the following mechanisms of evaporation are considered:

- Real time diurnal emissions (sum of diurnal emissions and resting losses)
- Hot-soak emissions
- Running losses

The aim of the evaporative emissions work was to review existing emission factor models and to perform measurements to fill some of the main gaps. Following this work, the most suitable model approaches were selected and - where possible – the model parameters were adapted to the results of the measurements.

From the literature and the measurements, it was possible to cover the following categories of petrol vehicle:

- Cars - pre-Euro I
- Cars - Euro I and II
- Cars - Euro III and IV
- Cars - Euro I to Euro IV with failures in the fuel system (leakages)
- Motorcycles (>50 cc cylinder capacity)
- Mopeds (<50 cc cylinder capacity)

The only new measurements were conducted on Euro III and Euro IV cars without failures in the fuel system. For this vehicle category, no measurements on emission factors have been previously available in Europe. The vehicles were measured over the standard European and US test programmes with different temperature cycles, in order to validate European and US models. The USEPA data can be considered to be representative of European vehicles where the corresponding vehicle categories are selected (controlled carbon canisters were introduced in the US much earlier than in Europe). Thus, the ARTEMIS model makes use of the data from the extensive measurement programmes in US since the three cars tested in ARTEMIS are a much too small sample to be representative for Europe. Due to different type approval tests in EU and US, the data from USEPA included in the ARTEMIS model may result in an underestimation for hot cycles and for parking durations longer than 24 hours, if the carbon canisters in European cars are on average smaller than those in US. However, no corresponding data on the fleet and no data on the numbers of vehicles parked for multiple days are available. Also, the rate of cars with failures in the fuel system was gained from US field tests since it is not known for Europe at all. Due to these shortcomings, a more extensive measurement programme is recommended. The actual data do not allow an estimation of uncertainties to be made. However, we assume that the new model is more accurate than the old ones, which were not based on actual measurements at all. Data for light goods vehicles (<3,500 kg maximum gross vehicle weight) are not available, and therefore the formulae for passenger cars are used for this category. Hydrocarbon emissions from the manipulation of fuel during refilling are not included in the model.

The ARTEMIS model is the first update of a European model for evaporative emission factors since 1993. In general, the actual measurements showed that evaporative emissions clearly decreased from pre-Euro I to Euro III and Euro IV, although emission factors for Euro III and Euro IV seem to be higher than predicted by the older models (COPERT and RWTÜV). The measurements showed a good performance for Euro III cars in all test cycles. Only a car with a small carbon canister showed a clear increase in evaporative emissions when the temperature and/or the test duration was longer than defined in the European type approval procedure.

A comparison of the existing models and the available measurements showed that both MOBILE 6 and CORINAIR do meet the measured data on hot-soak and diurnal evaporative emissions with comparable accuracy. The MOBILE 6 method is suggested for simulating hot-soak and diurnal emissions, since it is based on many more vehicles measured and on a more physically sound approach than CORINAIR. Thus it is assumed that the reliability of vehicle categories and ambient conditions not measured in the ARTEMIS programme will be higher when using the MOBILE 6 model. The parameters of the MOBILE 6 model were then converted into SI units and the relevant vehicle categories to cover European legislation were selected (pre-Euro I to Euro IV. Several simplifications were made here, since MOBILE 6 includes a very extensive set of vehicle categories when combining years of first registration and different sources of failures in the fuel system. Running losses should be calculated based on a modification of the CORINAIR methodology.

Compared with the existing European models, a category of ‘vehicles with failures’ was newly introduced, although no data on their share in the European fleet is available. Since there is no indication that the European vehicles may have fewer failures than the US fleet, the rates of failures found in USEPA field tests are assumed for Europe. All the available measurements on European vehicles were performed rather exclusively on quite new cars with low mileages driven. Thus no ‘high emitters’ were included in the European data set, yet. The approach with ‘vehicles with failures’ is open to include future research on this topic. Such a research programme on the conditions of the fuel systems of older European cars would be very important if more accurate emission factors are needed for evaporative emissions of vehicles in the future.

The results show that evaporative emissions of Euro III and IV are substantially lower than for Euro I and II. Reasons for this can mainly be found in the more stringent emission legislation and the advanced test procedure. This leads to the introduction of more sophisticated and durable technologies, which are monitored by on board diagnostic systems. The main remaining sources of evaporative emissions in road traffic are thus old cars and all the two wheelers without a carbon canister and newer cars with failures in the fuel system. As described, the shares of vehicles with failures are only based on assumptions. The introduction of failure rates for the vehicles as well as the different model approaches lead to evaporative emission levels which are higher than those provided by the European CORINAIR model. For typical driving of a vehicle on a summer day, the new ARTEMIS model gives approx. 145% higher evaporative emissions for the average pre-Euro I car, +360% for the Euro I and II cars and +80% for Euro III and IV cars than compared to the CORINAIR approach. Since CORINAIR does not include emissions measured within the last decade and ARTEMIS is only based on three new European cars measured, it is obvious that the database is much too small to establish a really reliable model on evaporative emissions.

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B9 VALIDATION

B9.1 Background and objectives

This Section of Part B describes the ARTEMIS work on the validation of emission factors for road transport, based upon measurements conducted in three tunnels. The text is a summary of the report by Rodler *et al.* (2005).

As emphasised earlier, the emission behaviour of road vehicles is influenced by many different parameters, including emission standard, vehicle technology, vehicle weight (especially for HDVs), *etc*. Hence, a large number of laboratory tests are required in order to obtain statistically reliable emission factors. Furthermore, it is desirable to use alternative methods to validate the emission data from vehicle and engine tests, and to adjust them to real-world conditions.

Road tunnels – which can effectively be considered as large laboratories – can be used to determine emission factors for in-service vehicles under real-world conditions. Due to the limited dispersion and dilution conditions in the tunnel environment, pollutant concentrations tend to be higher than in normal ambient air. In addition, external meteorological influences are reduced. Pollutant concentrations increase along the length of a tunnel as the emissions from the traffic accumulate. An average emission factor for a pollutant ***i*** and all the traffic passing through a tunnel during a time period ***t*** can therefore be derived using Equation 1 (Weingartner *et al.,* 1997):

$$EF_i = \frac{(C_{i,exit} - C_{i,entrance}) \cdot v_{air} \cdot t \cdot A}{L \cdot N} \qquad \text{(Equation B9-1)}$$

where:

EF_i	=	Total emission factor for pollutant ***i*** (g vehicle^{-1} km^{-1})
$C_{i, exit}$	=	Concentration of pollutant ***i*** at tunnel exit (g m^{-3})
$C_{i, entrance}$	=	Concentration of pollutant ***i*** at tunnel entrance (g m^{-3})
v_{air}	=	Velocity of the air in the tunnel (m s^{-1})
t	=	Time duration of sampling (s)
A	=	Tunnel cross-sectional area (m^2)
L	=	Tunnel length (km)
N	=	Number of vehicles passing during time ***t***

The above equation has been employed extensively to derive emission factors in various tunnel studies (*e.g.* Gillies *et al*., 2001; Staehelin *et al*., 1997; John *et al*., 1999). The measurement set-up depends on the tunnel ventilation system. For a simple longitudinal ventilation system, instruments should be placed where the highest concentrations are to be expected, and the volume flow can be defined exactly – this is normally near the exit portal. In tunnels with transverse ventilation, pollutant concentrations are more or less constant over a given ventilation section, and the concentration measurements therefore have to be carried out both in the ventilation section and at the entrance to the ventilation system.

In ARTEMIS, measurements in three different road tunnels were undertaken:

(i) The Lundby tunnel (Gothenburg, Sweden)
(ii) The Plabutsch tunnel (Graz, Austria)
(iii) The Kingsway tunnel (Liverpool, United Kingdom)

The main objective of this part of the ARTEMIS work was to derive new real-world emission factors in order to improve the accuracy of road traffic models. The measurements had to be processed, and a statistical analysis was undertaken for each tunnel in order to determine emission factors for different vehicle categories. It was therefore necessary to examine cross-correlations between pollutants, source profiles and traffic/ventilation data. The emission factors from the tunnel measurements were then compared with existing emission factors for the actual traffic conditions recorded during the tunnel measurement campaigns.

B9.2 Experimental methodology

The three ARTEMIS measurement campaigns are summarised below. For each campaign, a brief description is provided of the tunnel used, the monitoring sites, and the measurements undertaken. In each tunnel various regulated and unregulated pollutants were measured, and a range of instruments was used. Nevertheless, the monitoring methods were broadly similar in the different tunnels, and these are listed in **Table B9-1** to avoid repetition later in the Section.

Table B9-1: Pollutants measured and instruments used in each tunnel.

Pollutant	Method	Tunnel		
		Lundby	Plabutsch	Kingsway
NO_x	Chemiluminescence	✓	✓	✓
CO	NDIR	✓	✓	✓
CO	UV-resonance-fluorescence		✓	✓
CO_2	NDIR	✓	✓	✓
CO_2	GC	✓	✓	✓
HC/NMHC	FID	✓	✓	✓
THC	FID	✓	✓	✓
NMVOC	GC	✓	✓	✓
SVOC	Tenax	✓		
N_2O	GC	✓	✓	✓
SF_6	FTIR	✓	✓	✓
SF_6	GC	✓		
SF_6	Bag samples	✓		
PM_{10}	TEOM	✓		
PM_{10}	Filter	✓		
$PM_{2.5}$	TEOM		✓	✓
$PM_{2.5}$	Filter	✓		
$PM_{1.0}$	Filter	✓	✓	✓
PM size distribution	SMPS	✓	✓	✓

B9.2.1 Lundby tunnel

Tunnel description

The Lundby tunnel is located in the city of Gothenburg and has two bores carrying two lanes of traffic in each direction (eastbound and westbound). The tunnel has a length of approximately 2 km, and each bore has a cross-sectional area of around 65 m². The ARTEMIS measurements were conducted in the south bore of the tunnel (eastbound). When driving through the tunnel from west to east, there is a 3.5% downhill gradient between the entrance portal and a point 900 m into the tunnel. Between 900 m and 1,500 m into the tunnel there is an uphill gradient of 0.25 %, and between 1,500 m and the exit portal there is an uphill gradient of 4%.

The ventilation system has two separate sub-systems: (i) longitudinal ventilation throughout the whole tunnel, which consists of 40 fans in each bore, placed in pairs along the ceiling and (ii) an axial ventilator in a vertical shaft 400 m from the eastern portal, which removes exhaust air from both bores of the tunnel. Normally, the two bores of the tunnel are self-ventilated due to the piston effect of the traffic. When traffic flows are high, the wind speed in the tunnel is usually between 2.5 m/s and 3 m/s. When the traffic flow is low, the wind speed decreases to between 1 m/s and 1.5 m/s. The jet fans are used occasionally, whereas the vertical ventilation system works only in the case of an emergency. The jet fans and the vertical ventilation system can be run separately or together, and the jet fans can be operated either all at once (40 fans), or with just one of each pair running (20 fans). The reason for using forced ventilation is that a high traffic flow combined with low speeds can lead to high concentrations of NO_2 in the tunnel.

Measurements

The ARTEMIS measurement campaign was carried out in Lundby tunnel between 23 and 30 March 2001. The measurements were conducted at three sites in the south bore of the tunnel. **Figure B9-1** shows the tunnel, its ventilation, and the measurement sites. No mechanical ventilation was used during the whole measurement campaign, and therefore the ventilation could simply be treated as longitudinal.

In the Lundby tunnel a split in the air flow is to be expected at the location of the vertical ventilation shaft. Therefore, air pollution monitoring equipment was installed at this specific location (Site 3 in **Figure B9-1**). Pollutant concentrations in the incoming 'fresh' were measured at Site 1 in **Figure B9-1**. Additional instrumentation was installed in the cavern of the main ventilation system (Site 4) in order to measure NO_x and SF_6 so that the air flow through the shaft could be determined. From time to time, measurements with an FTIR system were conducted at several sites. In addition to the data measured within the campaign, data were provided by the tunnel operator. The tunnel operator stored NO_2 and NO data from a permanent DOAS instrument, and also recorded wind speed and the number of vehicles passing through the tunnel using automatic systems. However, no distinction was made between light-duty and heavy-duty vehicles in the vehicle count, and so a video survey was conducted at the tunnel exit in order to determine the fleet composition. A list of registration numbers was sent to the Swedish Car Register so that vehicle details could be obtained.

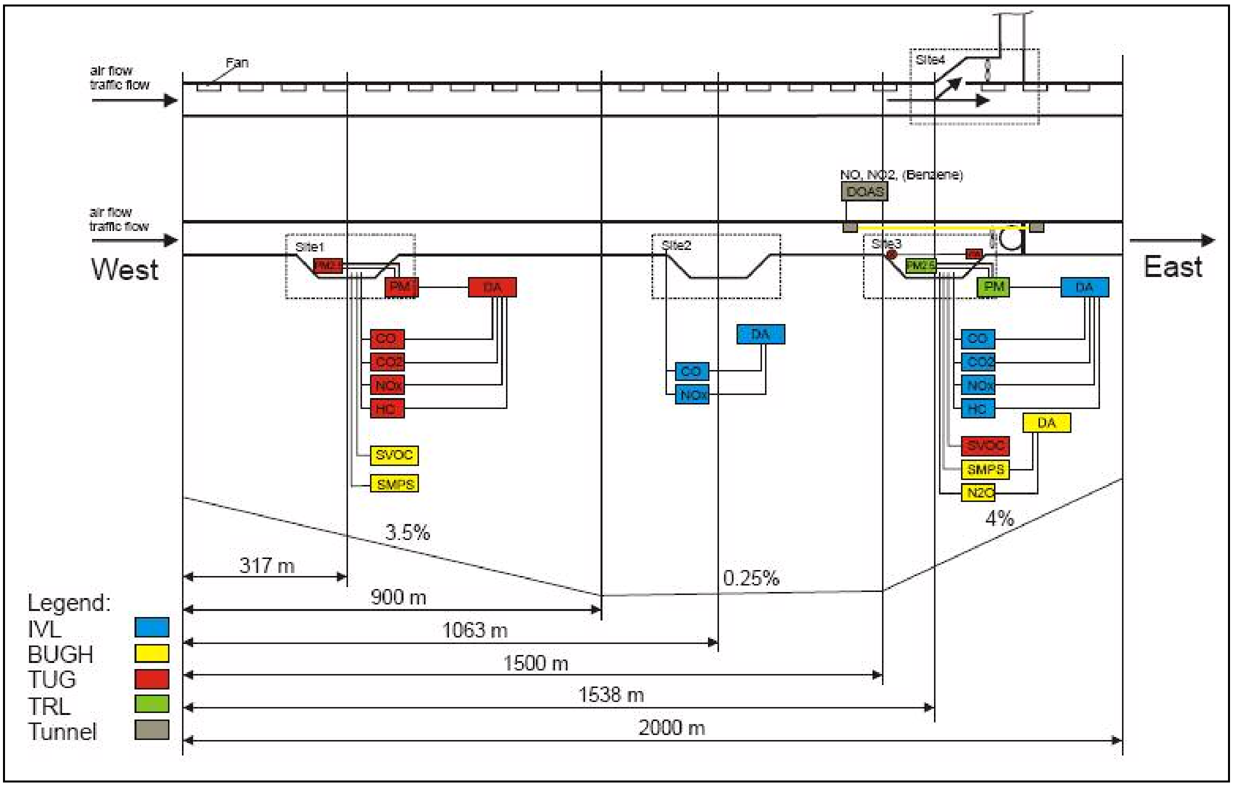

Figure B9-1: Measurement sites and pollutants in Lundby tunnel.

Wind speed was measured using two ultrasonic FLOWSIC instruments at different locations. The FLOWSIC measures the mean air flow velocity across the entire width of a tunnel. The device can measure flow velocities of up to 20 m/s with a typical accuracy of ± 0.1 m/s. Sender and receiver units are mounted on both sides of a tunnel at a fixed angle of inclination to the air flow. The units contain piezoelectric ultrasonic transducers which operate alternately as transmitter and receiver. The transit time of the ultrasonic pulses varies according to the flow velocity. One instrument was the permanently installed FLOWSIC in the middle of the tube. The other FLOWSIC was installed at Site 4 so that the flow via the vertical shaft could be determined.

B9.2.2 Plabutsch tunnel

Tunnel description

The Plabutsch tunnel serves as a bypass around the city of Graz in Austria. With a total length of 9,755 m, it is the longest tunnel on the Pyhrn A9 motorway that connects the Balkan states to Central Europe, and is the second longest tunnel in Austria. The gradient of the tunnel varies from -1% to +1%, and the speed limit is 80 km/h. The bore has a cross-sectional area of approximately 50 m^2. **Figure B9-2** shows a longitudinal profile of the tunnel. It is divided into five ventilation sections, each having a length of around 1,950 m, and is equipped with a transverse ventilation system with a maximum air flow rate of 200 m^3/s fresh air (and waste air) in each section. Section 1 is ventilated by a station located at the northern portal. Sections 2 and 3 are ventilated by a 240 m-high shaft (north shaft), and sections 4 and 5 by a 90 m-high shaft (south shaft).

Measurements

The measurement campaign in the Plabutsch tunnel took place between 5 and 13 November 2001. The measurements were undertaken in the east bore of the tunnel, which at the time carried bi-directional traffic. The transverse ventilation used in Plabutsch tunnel ensures an evenly distributed pollutant concentration over the whole length of each ventilation section. In order to derive emission factors for the vehicles passing through a given ventilation section, pollutant concentrations must be measured both in the tunnel section and in the fresh air from the ventilation shaft. The throughput of fresh air and waste air is also required. Furthermore, the tunnel measurement site has to be located where there are no changes in the road gradient, so that a constant emission behaviour can be assumed. Given these considerations, the optimum location for the in-tunnel measurements was identified as being ventilation section 3 (Site 1 in **Figure B9-2**). Site 2 was used for the measurement of the incoming fresh air.

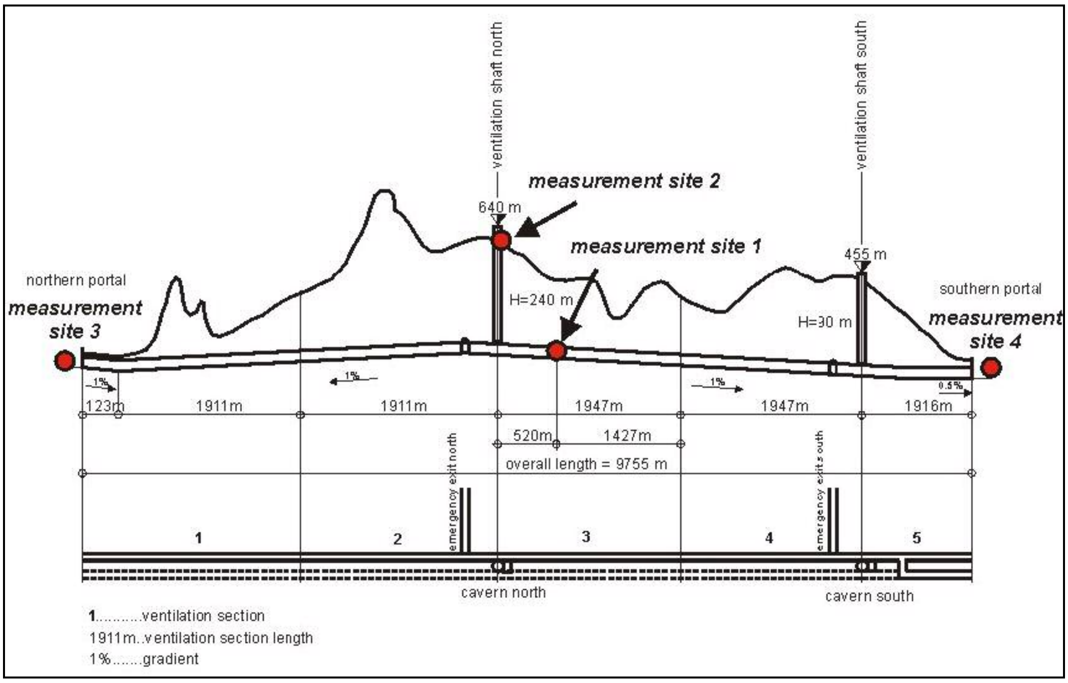

Figure B9-2: Longitudinal section of the Plabutsch tunnel and locations of measurement sites.

Measurement Site 1 was located approximately 4,465 m inside the tunnel. An emergency parking bay in ventilation section 3 was used to park a mobile air quality monitoring laboratory which housed analysers for NO_x, CO, HC and an SMPS[39]. PM measurements with a TEOM (PM_{10}), and black carbon (BC) where also conducted at this site. The sensor unit of the TEOM was erected close to the street within the parking bay, and the PM_{10} inlet was installed at around 2 m above ground level. A small maintenance room behind the parking bay was used to house a NMVOC monitor and the CO_2 and N_2O analysers. As Site 1 was located 520 m from the north ventilation shaft, there was unlikely to be any influence from ventilation sections 2 and 4. Another SMPS was installed at the bottom of the north ventilation shaft to analyse air from the waste air duct. At this location the exhaust air is a mixture of all the air drawn in into the exhaust duct over a 2 km section of tunnel. Measurement Site 2 was located at the top of the north ventilation shaft, where measurements of NO_x, CO, CO_2 and HC concentrations in the incoming fresh air were conducted. A NMVOC monitor and one SMPS where also installed at this Site. Measurement Sites 3 and 4 were located at both ends of the tunnel.

Any additional data needed for the emission factor calculations were provided by the tunnel operator, including the traffic flow, with a distinction between LDVs and HDVs, and the volume flows of fresh and exhaust air for each of the five ventilation sections. As in the Lundby tunnel, a video survey was conducted on two days of the campaign to provide more detail on the composition of the traffic.

B9.2.3 Kingsway tunnel

Tunnel description

The choice of an appropriate UK tunnel for use in ARTEMIS was rather limited. Tunnel length, age and complexity, as well as the availability of space for monitoring equipment, were factors complicating the selection. Following a consideration of such factors, the Kingsway tunnel in Liverpool was selected for the third ARTEMIS study.

The Kingsway tunnel is a toll tunnel. Having opened in 1971, it is the newer of the two tunnels under the river Mersey connecting Liverpool in the east to Wallasey in the west. The tunnel incorporates two circular bores, which are 2,480 m long. Each bore carries two lanes of uni-directional traffic, with the north bore carrying traffic from Wallasey to Liverpool, and the south bore carrying traffic in the opposite direction. When cleaning or other tunnel maintenance operations are in progress in one bore, the other bore is run in bi-directional mode. The speed limit in the tunnel is 40 mph (64 km/h).

The tunnel ventilation is semi-transverse. Clean air enters the tunnel via the two ventilation shafts and via the portals. The air from the ventilation shafts is fed into a sub-floor duct and permeates into the tunnel through vents along its length (**Figure B9-3**). The vents are designed to allow an even flow of inlet air along the tunnel length at a maximum ventilation rate. Exhaust air is removed via the ventilation shafts, and can also leave via the portals. However, at times of heavy, congested traffic, jet fans mounted in the tunnel crown are activated. The tunnel is fitted with equipment, at several locations, to

[39] SMPS = Scanning Mobility Particle Sizer, an instrument for measuring particle size distributions.

monitor carbon monoxide levels and visibility. These two criteria are used to adjust the ventilation system, and an alarm and manual control system is in place.

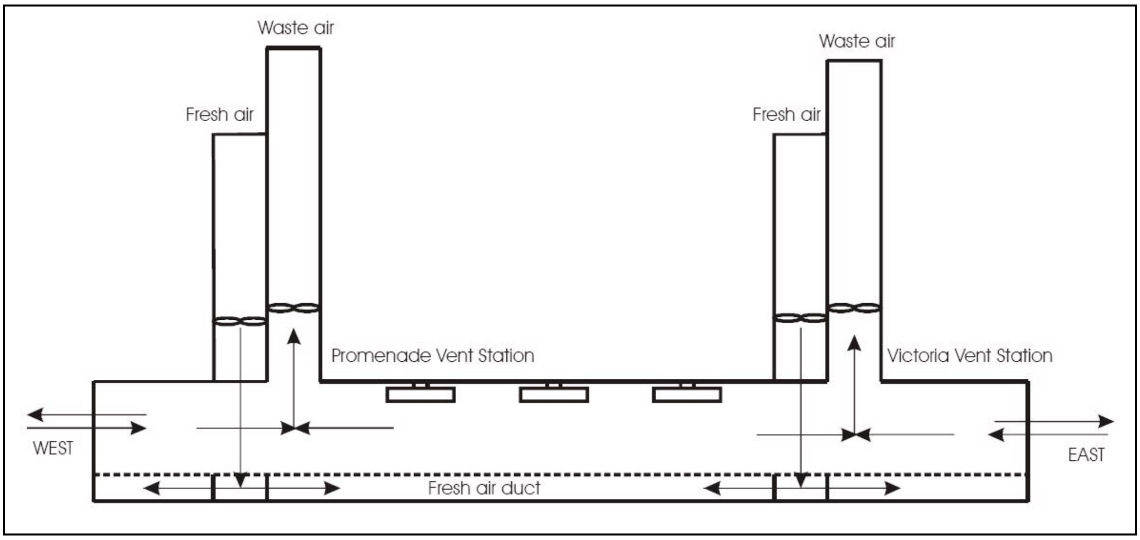

Figure B9-3: Ventilation system in Kingsway tunnel.

Measurements

The measurement campaign in the Kingsway tunnel took place between 7 and 15 February 2003. The monitoring sites, which are shown in **Figure B9-4**, were:

(i) Site 1: Inside the 'Promenade' ventilation station.
(ii) Site 2: In the tunnel near to the Wallasey portal (invert under road).
(iii) Site 3: Inside the 'Victoria' ventilation station.
(iv) Site 4: In the tunnel near to Liverpool portal (invert under road).

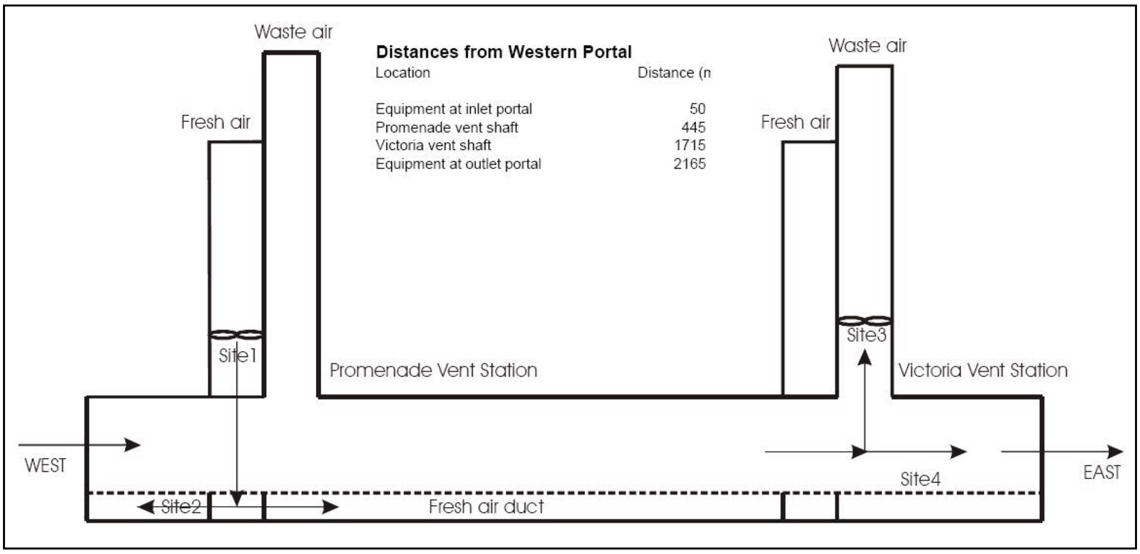

Figure B9-4: Measurement sites in Kingsway tunnel.

During the ARTEMIS experiment, the ventilation was configured in a way which would encourage the longitudinal flow of air through the north bore of the tunnel in the direction of the traffic. At the Promenade ventilation station the inlet air fan was switched on and the exhaust fan was switched off. At the Victoria ventilation station the exhaust fan was switched on and the inlet fan was switched off. The jet fans in the tunnel bore were not used for extended periods.

To measure pollutant concentrations in the incoming fresh air, analysers for CO, CO_2, NO_x and HC where installed inside the Promenade vent station. The sampling of these gaseous components required a sampling line to be fitted through a hole in the ventilation shaft. A SMPS and a TEOM equipped with a $PM_{2.5}$ sampling head were also operated at this location. The sensor unit of the TEOM was erected close to the shaft, with the $PM_{2.5}$ inlet installed around 4 m above ground level and connected to the sensor unit with a stainless steel line (**Figure B9-5**). Pollutant concentrations in the air entering the tunnel through the inlet portal (Wallasey) were measured at Site 2. The instruments (analysers for CO, CO_2, NO_x and HC) where installed in the sub-floor duct (**Figure B9-6**), and a sampling line was fed into the tunnel through a vent. PM measurements ($PM_{2.5}$) were performed at kerbside in the tunnel. The sensor unit of the TEOM was erected on the footway close to the road. The $PM_{2.5}$ inlet was installed around 2 m above ground level. The measurements of polluted tunnel air were conducted at Site 3, which was located inside the Victoria vent station. Analysers for CO, CO_2, NO_x, N_2O, THC and NMVOC, and a TEOM equipped with a $PM_{2.5}$ sampling head were operated at this location, as at Site 1. At Site 4, located at the outlet portal (Liverpool) in the sub-floor duct, analysers were installed to measure CO, CO_2, NO_x and HC, the setup being similar to that at Site 2.

Figure B9-5: Promenade vent station – sampling through the fresh air shaft

Figure B9-6: Wallasey portal – Site 2

In the Kingsway tunnel, the flow and composition of the traffic in the north bore were determined primarily from the hourly toll information collected by the tunnel operator at the Wallasey portal between 8 and 13 February 2003. For tolling purposes, vehicles passing through the Kingsway tunnel are separated into four categories, each including several different types of vehicle. The toll information was used to calculate the total eastbound traffic flow and the proportion of HDVs in the traffic during each hourly period. Again, video surveys were conducted to identify vehicle registration numbers, and vehicle details were obtained from the UK Department for Transport. Speed profiles were measured using vehicle-based equipment. The air flow in the north bore of the Kingsway tunnel was recorded continuously using two FLOWSIC instruments. Air flows were also recoded in the ventilation shafts using Pitot tubes.

B9.3 Experimental results

The results of the experimental work are summarised only briefly here. The results are presented in more detail by Rodler *et al*. (2005), and are available on request from the Technical University of Graz.

B9.3.1 Lundby tunnel

The air pollution measurements in the Lundby tunnel generally ran smoothly without any major loss of data. For example, **Figure B9-7** shows NO_x concentrations measured at the inlet (Site 1), middle (Site 2) and outlet (Site 3) locations. The overall average amount of HDV traffic during the weekend was very low (5 %), and on weekdays it was not more than 13%. The wind speed measurements obtained from the two FLOWSICs were very similar, and hence the air flow via the vertical stack could be considered to be negligible. However, some of the wind speed measurements were considered to be problematic, and probably not representative. Therefore SF_6 was used as a tracer, and with the measured mixing ratio of SF_6 the wind speed data could be estimated. This work was conducted by ETH-Zurich, and is described by Colberg *et al.* (2004).

B9.3.2 Plabutsch tunnel

During the Plabutsch tunnel measurement campaign the CO, NO_x and PM_{10} measurement equipment performed well. The NO_x data are shown in **Figure B9-8**. A problem arose with the CO_2 analyser at Site 1. The CO_2 analyser from the inlet site was therefore moved to the tunnel site, as the CO_2 concentration in the fresh air remained virtually constant at around 390 ppm, and it was assumed that no further monitoring of the CO_2 in the fresh air was required. A problem also arose with the HC measurement. When the impactor of the SMPS, which was operated in the container at tunnel site, was cleaned with some cleanser containing hydrocarbons, the HC analyser was affected by this. Following a validation exercise it was possible to correct this problem. From the traffic data recorded by the tunnel operator, only a distinction between passenger cars and heavy-duty vehicles was possible, whereby a car with trailer was counted as a truck and motorcycles were counted as cars. However, it could be assumed that there were effectively no motorcycles during the period, and the proportion of cars with a trailer was very low. The traffic flow was more or less equivalent in both directions, with the exception of a single day which was a public holiday. The proportion of HDVs in the traffic was found to be around 4% at the weekend, and around 20% on weekdays. As far as the air flow rate in the tunnel was concerned, the maximum flow rate of 200 m/s was used for most of the measurement campaign.

B9.3.3 Kingsway tunnel

Because of the complex ventilation system in the Kingsway tunnel, a large array of instrumentation was required at four different sites. Due to the unfavourable location of some instruments, and problems with the availability of personnel, some substantial losses of data occurred. A number of assumptions were therefore required concerning flow rates and concentrations, otherwise data processing for emission factor analysis would have been difficult (Rodler *et al*., 2005). For example, few measurements were obtained at the inlet portal due to a failure of the data logger– this can be seen in the NO_x data in **Figure B9-9**. The FLOWSIC at the Wallasey portal also failed early in the campaign, and was replaced by a sonic anemometer. The Pitot tubes installed at the Promenade vent station also failed due to an exceedance of the measurement range of the pressure gauge. Therefore, the flows were calculated from fan settings provided by the tunnel operator. The average proportion of HDVs in the traffic during the measurement period was found to be around 5%, and the traffic speed did not vary greatly outside peak periods.

B9.4 Calculation of emission factors

The road tunnel measurements performed in ARTEMIS provided information on real-world emissions from vehicle fleets. The approach used to calculate average emission factors for the traffic was essentially that given in Equation 1. However, because of the fully transverse ventilation system in the Plabutsch tunnel, a slightly different calculation model has to be used for calculating emission factors. This was developed by TUG according to the results of two previous tunnel studies in the tunnel in 1998 and 1999 (Rodler and Sturm, 2000).

In the next step, multiple regression analysis was used to obtain emission factors for LDVs and HDVs, and for particular traffic situations. LDVs included passenger cars (PC) and light duty commercial vehicles (LDCV). Finally, the results were compared with the emission factors used in the respective countries, and the new ARTEMIS emission factors were checked. It has to be pointed out that for accurate comparisons detailed information on the fleet composition, vehicle speeds and loading factors for the HDV is required.

B9.4.1 Emission factors derived from tunnel measurements

The emission factors derived from the tunnel measurements are shown in **Table B9-2**. A statistical analysis of the data set obtained from Lundby tunnel study was conducted by ETH-Zurich (Colberg *et al.,* 2004). No CO emission factors are given for HDVs, as the proportion of HDVs never exceeded 30%. The emission factors for HDVs were obtained by extrapolation to 100%, and only yielded reliable estimates for NO_x because the emission factor is much larger than that for LDVs, which is not the case for CO and VOCs. No results were available for VOCs in the Lundby tunnel due to problems with the measurements. The results show a considerable effect of day of the week, this being most pronounced for NO_x and CO. This suggests that the LDV fleet may be considerably different on weekends and weekdays. The HDV proportion in the traffic was very small during the weekend compared with weekdays, which means that the confidence intervals are much larger. Furthermore, the HDV fleet is different at the weekend, as it mainly consists of coaches rather than goods vehicles.

The statistical analysis of the ARTEMIS data by Colberg *et al.,* 2004 revealed no significant differences between the emission factors of LDVs and HDVs for both CO and VOCs. Hence, no HDV emission factors for these two pollutants were given. Also, no distinction was made between the different road gradients, although random tests of 300 and 500 vehicles were used as an input to the statistical model. The results of the 500-vehicle tests are shown in **Table B9-2**. A further statistical analysis of the Plabutsch tunnel data was conducted by TUG. Emission factors were obtained for CO_2, CO and NO_x, and for both directions of traffic (road gradient +1%/-1%) by extracting factors for the different road gradients from the HBEFA2.1 for Austria.

The statistical analysis of the Kingsway tunnel data was undertaken by TUG. Emission factors were obtained for CO, CO_2, NO_x and $PM_{2.5}$, and for an average road gradient (-4%/+4%). The emission factors for PM2.5, which are not shown in **Table B9-2**, were 0.023 ± 0.006 g/vkm for LDVs and 0.366 ±0.07 g/vkm for HDVs.

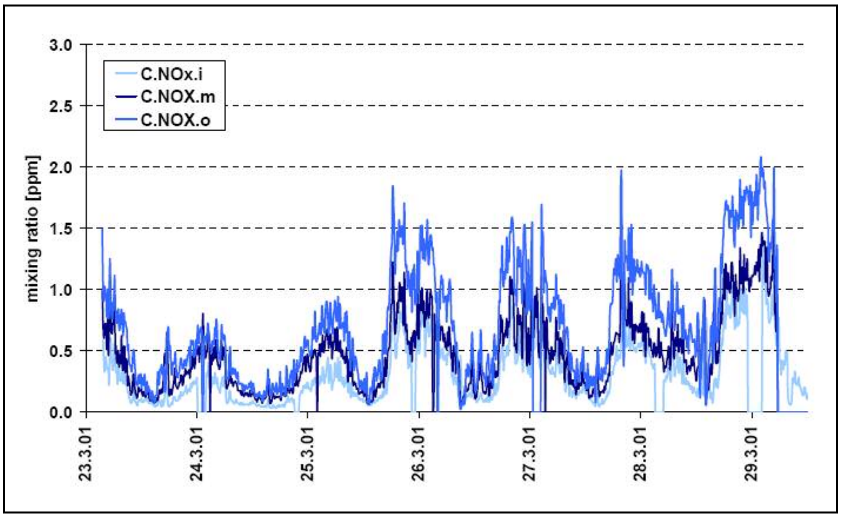

Figure B9-7: NO_x concentration at inlet (i), middle (m) and outlet (o) sites in the Lundby tunnel.

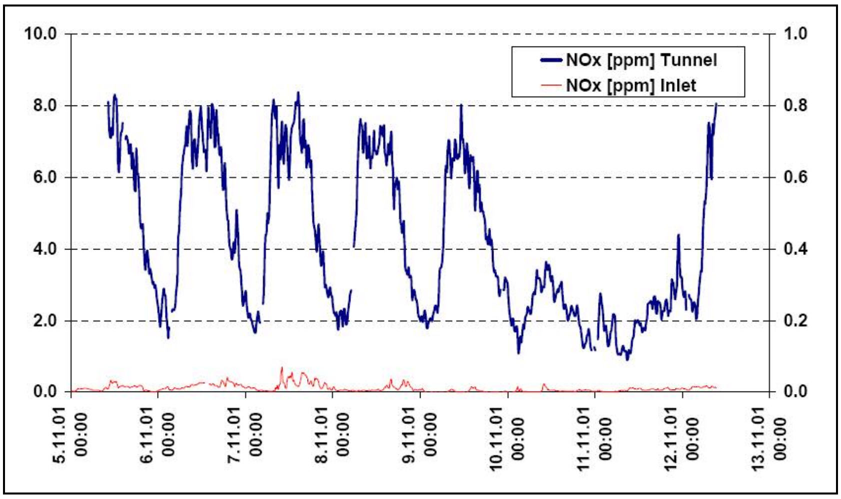

Figure B9-8: NO_x mixing ratio from Plabutsch study (inlet/tunnel).

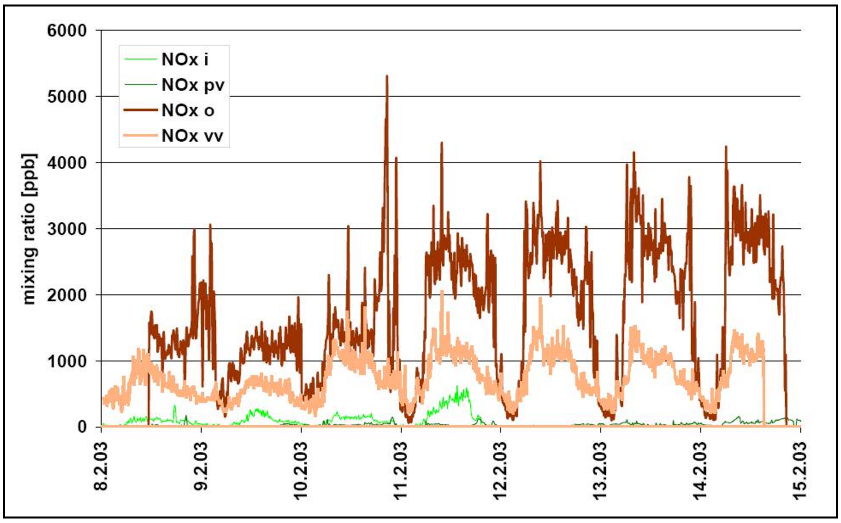

Figure B9-9: NO_x mixing ratio in the Kingsway tunnel.

Table B9-2: Emission factors derived from the tunnel measurements.

Tunnel	Road gradient	Average speed (km/h)	Period	Emission factor (g/km) with 95% confidence intervals							
				CO		VOC		NO_x		CO_2	
				LDV	HDV	LDV	HDV	LDV	HDV	LDV	HDV
Lundby (2001)	-2.7%	75	Weekday	2.0 (+0.5/-0.4)	-	-	-	0.31 (+0.13/-0.09)	1.12 (+0.95/-0.52)	-	-
			Saturday	3.2 (+1.0/-0.8)	-	-	-	0.42 (+0.17/-0.12)	1.56 (+1.85/-0.84)	-	-
			Sunday	2.7 (+1.7/-1.0)	-	-	-	0.46 (+0.21/-0.15)	1.73 (+1.89/-0.91)	-	-
	+0.6%	75	Weekday	2.0 (+0.8/-0.6)	-	-	-	0.36 (+0.07/-0.06)	11.2 (+0.7/-0.7)	-	-
			Saturday	3.3 (+1.5/-1.1)	-	-	-	0.3 (+0.05/-0.04)	9.3 (+1.3/-1.1)	-	-
			Sunday	2.7 (+1.3/-0.9)	-	-	-	0.32 (+0.05/-0.04)	10.1 (+1.1/-1.1)	-	-
Plabutsch (2001)†	-1%/ +1%	70	Weekday	0.98 (±0.11)	-	0.15 (±0.02)	-	0.75 (±0.2)	10.0 (±1.0)	-	-
			Saturday	0.67 (±0.07)	-	0.11 (±0.02)	-	0.49 (±0.01)	6.5 (±1.4)	-	-
			Sunday	0.67 (±0.08)	-	0.10 (±0.01)	-	0.37 (±0.06)	5.0 (±1.3)	-	-
Plabutsch (2001)‡	-1%		All	0.42 (±0.04)	1.39 (±0.17)	-	-	0.27 (±0.09)	8.32 (±0.025)	98.1 (±9.8)	694.1 (±29.8)
	+1%		All	0.83 (±0.08)	2.28 (±0.28)	-	-	0.39 (±0.13)	15.7 (±0.47)	135.7 (±13.6)	1397.7 (±60.1)
Kingsway (2003)	-4%/ +4%	65	All	1.73 (±0.05)	1.73 (±0.05)	-	-	0.61 (±0.05)	11.37 (±0.6)	188.5 (±14.6)	1311.1 (±173.7)

† ETH-Z analysis
‡ TUG analysis

B9.4.2 Comparisons with ARTEMIS emission factors and national models

Previous results from the Gubrist tunnel in Switzerland (Staehelin and Colberg, 2004**)** and the Plabutsch tunnel in Austria (Sturm and Rodler, 2000; Hausberger *et al.*, 2002) showed acceptable agreement for CO and total VOC with the Handbook of Emission Factors (HBEFA Version 1.2) (INFRAS, 1999), which is the most comprehensive road traffic emission model for Switzerland, Germany and Austria. For NO_x, the agreement was acceptable only for LDV only. HBEFA predicted much smaller emission factors for HDVs than the tunnel studies indicated.

Emissions calculated using tunnel measurements and ARTEMIS

The ARTEMIS emission model for road transport gives emission factors for particular traffic situations or average speeds. For each of the three tunnels, the emission factors calculated using the ARTEMIS model were compared with those derived from the tunnel measurements. A number of assumptions were required in the application of the ARTEMIS model, and these are described by Rodler *et al*. (2005). The results of the comparisons for CO_2 and NO_x, presented in terms of the total emission from traffic per km over 10-minute averaging periods, are shown in **Figures B9-10** to **B9-12**. In each graph, the tunnel-derived emission value ('measurement') is plotted on the *x*-axis, and the emission value derived using the ARTEMIS model ('calculation') is given on the *y*-axis. The results for CO are not shown, but are discussed below.

An important quality check of the model used to derive emissions from the tunnel measurements is the comparison between measured and calculated CO_2 emissions. Fuel consumption (or CO_2) is the variable which can be calculated with the greatest accuracy. If the calculated and measured CO_2 concentrations match, it can be assumed that boundary conditions like air flow and vehicle mix fit. For CO_2 in the Lundby tunnel (**Figure B9-10**), a regression fit to the data gave a moderate R^2 value (0.77), but a slope very close to unity. For CO, a R^2 value of 0.55 and slope of 0.80 were obtained, indicating that the ARTEMIS emission factors were, overall, lower than tunnel-derived emission factors. In the case of NO_x for the Lundby tunnel, the R^2 value and slope were 0.81 and 1.28 respectively, indicating that the ARTEMIS model was overestimating emissions.

In the Plabutsch tunnel (**Figure B9-11**) there was a good level of agreement between the ARTEMIS results and the tunnel results, with the regression fit to the data yielding an R^2 value of 0.90, and a slope of 0.96. However, the results for CO were less impressive (R^2 = 0.84, slope = 1.74), with the ARTEMIS calculation leading to an overestimation of CO of about 80%

compared with the tunnel measurements. On weekdays, NO_x emissions estimated using the ARTEMIS model were slightly lower than those derived from, the tunnel measurement, whereas during weekends the calculated emissions were slightly higher. The overall R^2 value and slope (0.90 and 0.92 respectively) were indicative of a good general level of agreement.

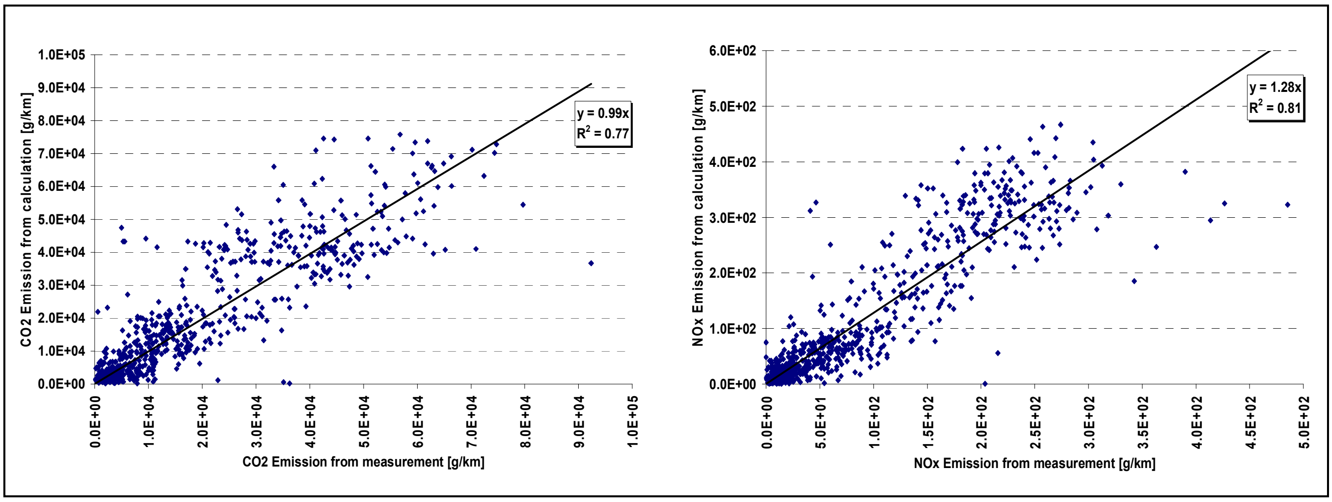

Figure B9-10: Correlations between measured and predicted pollutant emissions in the Lundby tunnel.

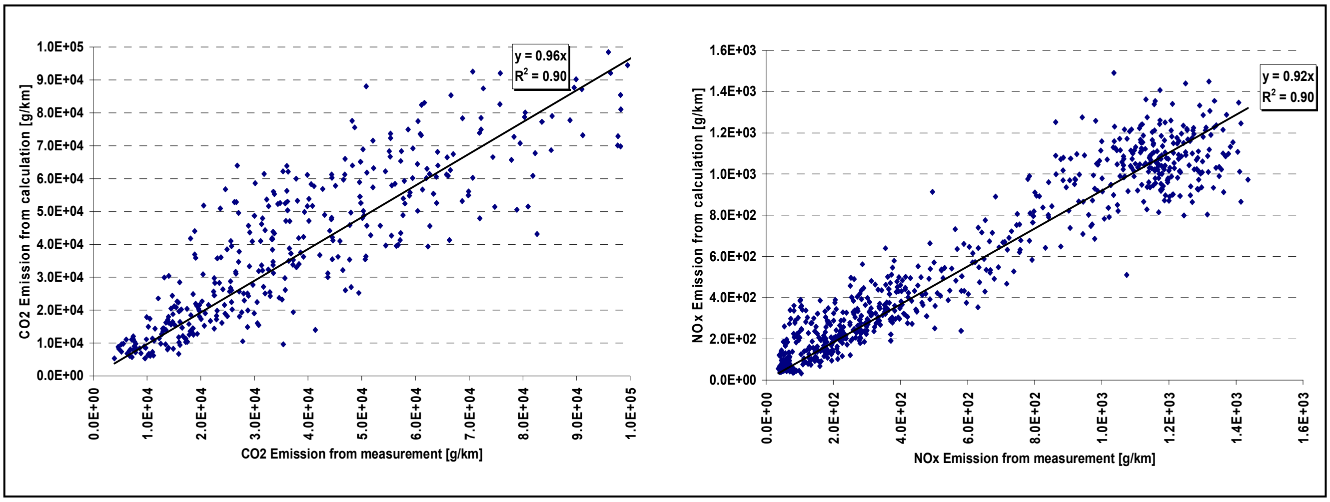

Figure B9-11: Correlations between measured and predicted pollutant emissions in the Plabutsch tunnel.

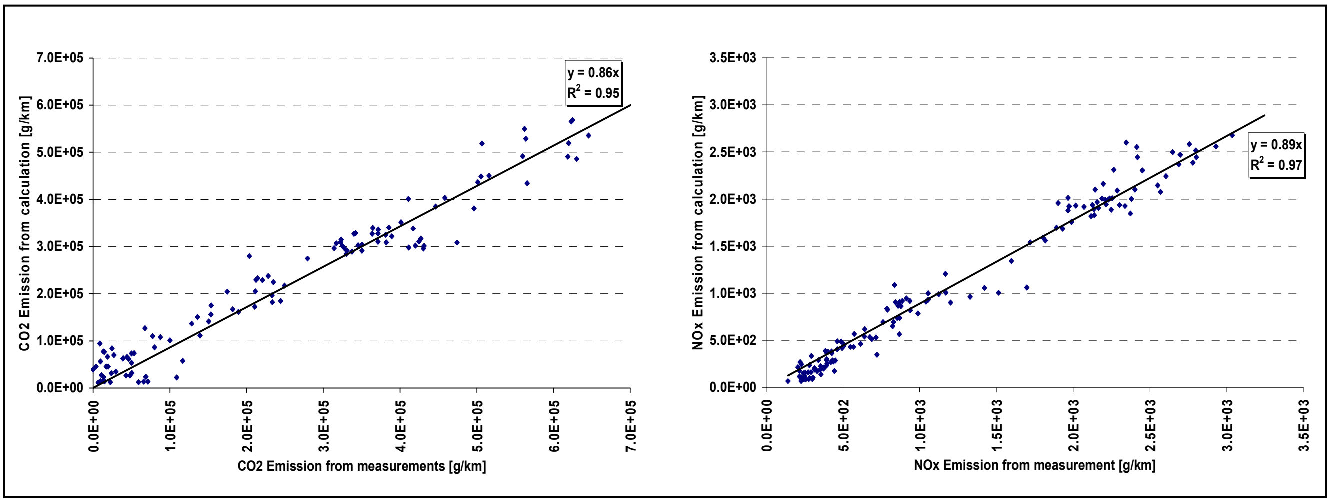

Figure B9-12: Correlations between measured and predicted pollutant emissions in the Kingsway tunnel.

The regression fit to the CO_2 emission data for the Kingsway tunnel (**Figure B9-12**), yielded an R^2 value and slope of 0.95 and 0.86 respectively. In other words, CO_2 emissions were, on average, underestimated by 15% using the ARTEMIS model. Again, CO was overestimated by the ARTEMIS model (slope = 1.58), although the correlation was high (R^2=0.94). For NO_x, during the whole period the calculated emissions were slightly lower than the emissions derived from the tunnel measurements (R^2 = 0.98, slope = 0.89). As the average proportion of HDVs in the Kingsway tunnel traffic is only around 5%, it can probably be concluded that the ARTEMIS emission factors for NO_x emissions from LDVs are too low in this case.

Emission factors for LDVs and HDVs compared with ARTEMIS and national models

For each of the three tunnels, the average emission factors for LDVs and HDVs derived from the ARTEMIS tunnel study were compared with and those from the ARTEMIS model. For the Kingsway and Plabutsch tunnels, comparisons were also made with the emission factors from national models.

The CO2 emission factors LDVs and HDVs derived from the Lundby Tunnel study showed a good agreement with those calculated using the ARTEMIS model. The measured LDV emission factor for CO also showed a good agreement with the ARTEMIS model, but for HDVs the tunnel measurements gave a higher emission factor than the model. The emission factors for NO_x obtained from the ARTEMIS data base, both for LDV and HDV, were higher (by around 20%) than those from the Lundby tunnel measurements. This was a different result to the other tunnel studies (Plabutsch and Kingsway), where the NO_x emission was underestimated using ARTEMIS data base. In the Lundby Tunnel vehicle fleet more than 50% of the HDV were articulated HGVs over 38 tonnes. As there was no information on the proportion of HGVs between 40 and 60 tonnes, an assumption had to be made. This assumption was that more than 90% of articulated HGVs were over 50 tonnes (which is probably too high), based on the Swedish mileage statistic. The exclusion of HGVs over 40 tonnes would therefore result in 10% lower NO_x emissions, but would still not explain the total overestimation.

For the Plabutsch tunnel, comparisons were made between the emission factors from the tunnel study, from the ARTEMIS model, and from the Handbook of Emission Factors Version 2.1 (INFRAS, 2004). The 'AB80_gebunden' driving pattern from HBEFA was used. For LDVs, the CO_2 emission factors derived from the tunnel measurements were the lowest, whilst those from the ARTEMIS model were the highest (almost 70% higher than the tunnel emission factors). The situation was reversed for HDVs, for which the HBEFA emission factors were the lowest whilst the ones measured in the tunnel were the highest. For CO, the LDV emission factors from ARTEMIS and HBEFA were too high (80% for ARTEMIS and 20% for HBEFA). On the other hand, in the case of NO_x it could be concluded that both models (in particular HBEFA) underestimate emissions if the tunnel measurements are taken to represent reality.

Comparisons between the emission factors derived from the Kingsway tunnel measurements, those from the ARTEMIS database and those from the national UK model (DMRB version 1.02g) are shown in **Figure B9-13**.

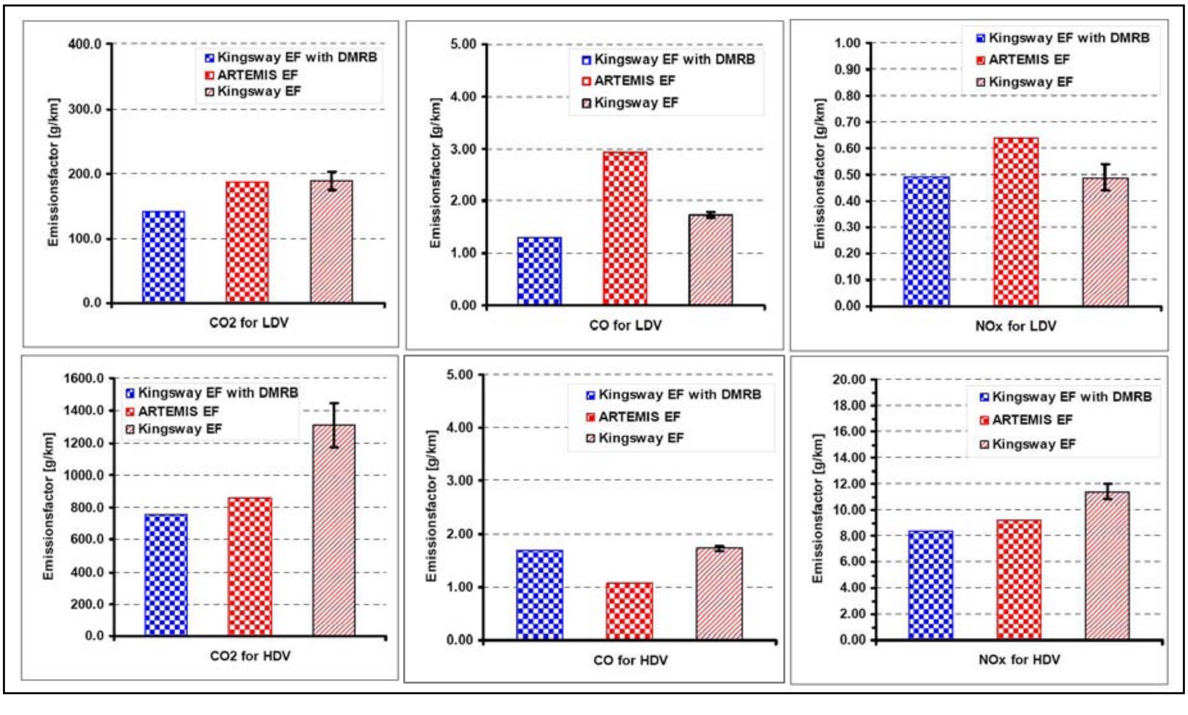

Figure B9-13: Comparison between CO_2, CO and NO_x emission factors from the national UK model (DMRB), the ARTEMIS model and the Kingsway tunnel data.

For the Kingsway tunnel the total numbers of vehicles in each category (PC, LDCV, Bus, Rigid HDV and Articulated HDV) were based upon the toll information. In order to disaggregate the toll information, average ratios were used (*e.g.* Proportion of LDVs which were PCs) for each hour based on the video surveys. Some assumptions were required to cover the hours outside the video surveys. The within-category distributions of Euro class and engine size were based on the video survey information. The same average profile was used for all time periods. Estimation of a diurnal speed profile based on the in-car pollution measurements, though these speeds did not vary much. For LDVs similar CO_2 emission factors were obtained from the analysis of the Kingsway tunnel measurements and the ARTEMIS model, whereas that derived from the DMRB was lower. For HDVs the CO_2 emission factor from the tunnel measurements was much higher than that from the two models. One reason for this could be the vehicle load, which is not well known and has a large influence on CO_2 emissions when combined with an uphill road gradient. The CO emission factor for LDVs from the ARTEMIS model was much higher than that from the tunnel data and DMRB (a similar result was obtained during the Plabutsch tunnel experiment). For HDVs the ARTEMIS model predicted slightly lower CO emission factors than the tunnel measurements and the DMRB. The LDV NO_x emission factors were in the same range for the ARTEMIS model and the tunnel study. The NO_x emission factor for HDVs is now much better than in former models, but still appears to represent an underestimate.

B9.5 Summary

In the ARTEMIS validation exercise for road transport, measurement campaigns were performed in three different European tunnels: the Lundby tunnel in Gothenburg, the Plabutsch tunnel in Graz, and the Kingsway tunnel in Liverpool. The three tunnels differed in terms of their gradient, vehicle fleet composition, traffic volume, and traffic speed. The main aim of the work was to determine real-world emission factors for various gaseous pollutants and PM for the whole vehicle fleet, as well as for LDVs and HDVs. The tunnel-derived emission factors were then compared with those in the ARTEMIS emission model and with national emission factors used at the time the tunnel studies were carried out.

In all three tunnel studies there was a good agreement between the measured CO_2 emission factors and the emissions derived from calculations using ARTEMIS emission factors. This can be considered as a check of the quality of the calculation approach, since CO_2 is the pollutant which can be determined with the highest accuracy. For the Lundby tunnel, the CO emission calculated with ARTEMIS model was much higher (60-70%) than the measured emission, and the NO_x emission calculated with ARTEMIS model was a little bit lower than the measured emission factor. In the Plabutsch and the Kingsway tunnel studies, the opposite results were obtained. However, the Lundby tunnel study mainly delivered emission factors for a strong downgrade (-3.5%), and is not really comparable with the Plabutsch and the Kingsway tunnel studies.

It could be concluded that the ARTEMIS CO emission factors for LDVs appear to be much too high, whereas the emission factor for NO_x and HDV is slightly too low, although much better than the emission factors formerly used in emission models. NO_x emissions are strongly dependent upon the vehicle load. Therefore, it is very difficult to calculate HDV emission for a specific traffic situation without knowledge of this important parameter. The CO emission factors for LDVs should be revisited, as the emission model HBEFA 1.2A (used until 2003) showed a much better agreement with the measurements than the new ARTEMIS database.

B9.6 References

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PART C: RAIL TRANSPORT

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C1 Background

This Part of the Report summarises the results of the rail transport work in ARTEMIS, and is adapted from the work of Sorensen *et al.* (2002) and Lindgreen and Sorensen (2005b).

The rail network in the EU15 countries has a total length of approximately 160,000 km. This represents a significant transport resource, as well as a large investment on the part of society. However, the contribution of the rail network to air pollution can be important at both the local level (*e.g.* for HC, CO, PM and NO_x) and on an international scale (*e.g.* for CO_2, SO_x, NO_x).

The diversity of rail traffic, and the difficulties associated with quantifying emissions from the sector, were identified in the MEET[40] project (European Commission, 1999). The difficulties identified in MEET remain relevant. For example, it was noted that each country in Europe has a national railway system and/or a number of individual systems which may be owned publicly or privately, and within each system there are likely to be a variety of applications. Passenger traffic varies from small urban trains - having a low maximum speed and frequent stops - to high-speed inter-city passenger trains with infrequent stops. Freight trains are used to carry a variety of goods, and again there is a range of operation - from shunting to high-speed international traffic. Activity data for passenger trains are available from timetables, but information on freight traffic scheduling and activity are more difficult to obtain. In addition, a large proportion of European rail traffic uses electrically-driven locomotives, and if emissions are to be allocated spatially and temporally the locations of power generation plant must be known. Further complications arise as a result of the international sale of electricity, as well as the multiple uses for the electricity produced by power stations (European Commission, 1999).

Previous rail emission models for inventory purposes have been based on empirical correlations between emissions, train type, operating speed and other simple variables. In the case of the MEET model, the distance between stops was used as a parameter, as it is related to acceleration (Jørgensen and Sorenson, 1997). In the TRENDS[41] model emissions were modelled using average emission factors for train fleets. Different emission factors were used for passenger and goods trains, and goods train emissions were estimated as a function of train size (Georgakaki *et al.*, 2002). Whilst such models may be sufficiently complex for a strategic study, their accuracy needed to be evaluated using a much larger set of data. The effects of parameters such as maximum speed and train length also needed to be investigated in greater detail, and the models modified accordingly.

In ARTEMIS, a new model has been developed for the prediction of energy consumption and emissions from rail transport. The ARTEMIS model builds upon the methodologies previously developed in MEET and TRENDS. Calculations can be made on the basis of knowledge of the distribution of train operating characteristics modes with respect to either time or distance. The model was evaluated for 18 passenger train routes and 12 goods train routes, and the model results were compared with measured engine power, energy consumption and emissions.

C2 ARTEMIS objectives

The overall aim of the rail transport work in ARTEMIS was to construct and validate a new model for the prediction of energy consumption and emissions. Some general considerations included the following:

(i) Since there is interest in evaluation at different spatial levels, it would be advantageous to have a single modelling method which could be used in this way. For example, when different models are used on different spatial scales, there is a risk of bias - a common model should reduce this risk. There should also be a smaller amount of time required for model development than in the case of several models for different spatial levels.

(ii) Ideally, a rail emissions model should have a strong technical basis. In other words, the fundamental physical processes determining energy consumption and pollutant emissions should be integral and identifiable parts of the model. This makes the model easier to upgrade in the future, as technological improvements in areas such as aerodynamics, train weight, rolling resistance, engine efficiency and emission control can be readily incorporated. This is because the influences of these parameters on operation, and therefore emissions and energy consumption, have been correctly included in the model. This approach has been very successful in the application of simulation models for engine control systems (Hendricks and Sorenson, 1990). Changes in operating conditions can also be addressed correctly, since the influences of variables such as acceleration and speed are correctly modelled from a physical point of view.

(iii) Users of rail transport models are likely to be non-experts involved in the compilation of local, national and international emission inventories, as well as political decision makers who use models to compare strategic transport options. It is therefore very important that emission predictions are accurate, are not subject to offset or bias, and have known statistical confidence levels. Given that the end-users are likely to be non-experts, model interfaces must be easy to use.

[40] MEET = Methodology for calculating transport emissions and energy consumption.

[41] TRENDS = Transport and Environment Database System.

The specific objectives of ARTEMIS can be summarised as follows:

(i) To re-evaluate the existing train classification scheme. In the MEET methodology five classes of train were used. These classes needed to be re-evaluated in order to determine whether they formed the most logical and relevant classification scheme. Of particular interest was the classification of goods trains, as these were grouped into just one category in MEET. The classes had to represent sectors which could be readily identified from a technical perspective, and for which the model user could obtain relevant traffic data.

(ii) To describe train operation. Factors relating to train classification and operation (speed, loading, gradient, distances between stops, *etc*.) needed to be investigated in detail. This process included an evaluation of the potential for using a range of operational descriptors in the modelling technique.

(iii) To model energy consumption and emissions. Detailed modelling and/or experimental data were required to determine energy consumption and emissions behaviour, but no new measurements were to be conducted. The overall goal of the model was that the calculated energy consumptions and emissions did not deviate by more than around 20% from experimental values.

(iv) To compile the results and construct the model. There was a need to develop relationships between the parameters required for modelling emissions and the parameters which end users could be expected to have at their disposal. The aim was to develop a model which would be open and accessible for future modification, and suitable for use in a database format similar to that being developed in TRENDS.

(v) To estimate future trends. Since strategic comparisons of transport modes involve systems to be constructed in the future, it was necessary to try to estimate future technological developments and trends.

C3 Model development and principles

C3.1 General approach

The overall objective of the rail transport work in ARTEMIS was to develop a model which could be used to calculate energy consumption and emissions for any train and any type of operation, based upon simple input data. In fact, the model calculates energy consumption and emissions on the basis of an operational matrix entered by the user. The rationale underlying this approach is described below.

The driving pattern of a train is typically described in terms of its speed as a function of either elapsed time or distance driven. Detailed measurements or simulation models can be used to describe train operation on a second-by-second basis, but it can often be difficult for model users to obtain and process this type of information. Furthermore, it was considered unlikely that users of the ARTEMIS model would be interested in detailed driving cycles, but rather operations on a larger scale. The ARTEMIS method was therefore designed to operate in a simpler and more transparent manner.

Train operation between any two locations consists of a number of periods of acceleration, operation at a roughly constant speed, and braking. In general, for a given type of train and operation the distribution of these ‘operational elements’ will be similar between every stop. By defining a distribution of operational elements it is possible to simulate any driving pattern. By dividing a driving pattern into speed intervals, and then further classifying these by acceleration, it is possible to describe the operation of a train. The ARTEMIS model therefore uses an operational matrix having speed and acceleration intervals. Each operational element of a driving pattern is described in terms of these speed and acceleration intervals. This principle has previously been used to model road vehicle emissions. The size of the intervals in the distribution matrix is important for the accuracy of the method. Since the speed-time distribution of operating conditions is not usually available for train operation, the model has been developed to include a spatial distribution. In other words, the operation is described by the percentage of the total distance travelled that a train operatives within a given range of speeds and accelerations. This enables a calculation based on the analysis of timetable operation, where distances are known.

Energy consumption and emission values are calculated using driving resistances, and this is explained in more detail in the following Sections. For a given train, steady-state driving resistances are proportional to the speed of the train, and the forces required for acceleration are directly proportional to the acceleration. Thus, by specifying the speed and acceleration of the train, all the forces involved in train movement on a level line can be obtained for each matrix element. The energy consumption at the wheels is equal to the product of the driving resistance multiplied by the driven distance. For the determination of the driving resistance and energy consumption, the average value of each is used for the calculation of the energy consumption and emissions for any operation point that lies within the limits of the matrix element. For an entire driving pattern, the total energy consumption can be estimated using a distribution matrix for the elements, that is a distribution of driving conditions, and then summing the weighted energy consumption of the entire operation. Such a model includes the assumption that all operation modes are independent of each other, and that the emissions and fuel consumption from operation at any condition are independent of any previous operating conditions. Under these assumptions, a driving pattern consisting of a series of operating conditions can be analysed using the statistical distribution of the operating conditions. This also means that it is not necessary to know the actual driving pattern, but only how frequently specific operating conditions occur, and the model can be used for any size of network, from an individual train route to a large network. This can, in principle, also be done independently of route length, the only restriction being that the route has an adequate length to give a statistically relevant distribution. The same model, technologically based, can be used for individual trains on short routes, train fleets on long routes, for single runs, or annual averages. For different types of trains the physical parameters must be changed, but since the physical parameters of the train are directly accessible this is readily accomplished.

The principle of the model is shown in **Figure C-1**. **Figure C-1** shows that the driving pattern can be characterised on the basis of either driving time or distance. The latter may prove to be more useful for conditions where the geographical features of a railway not are available.

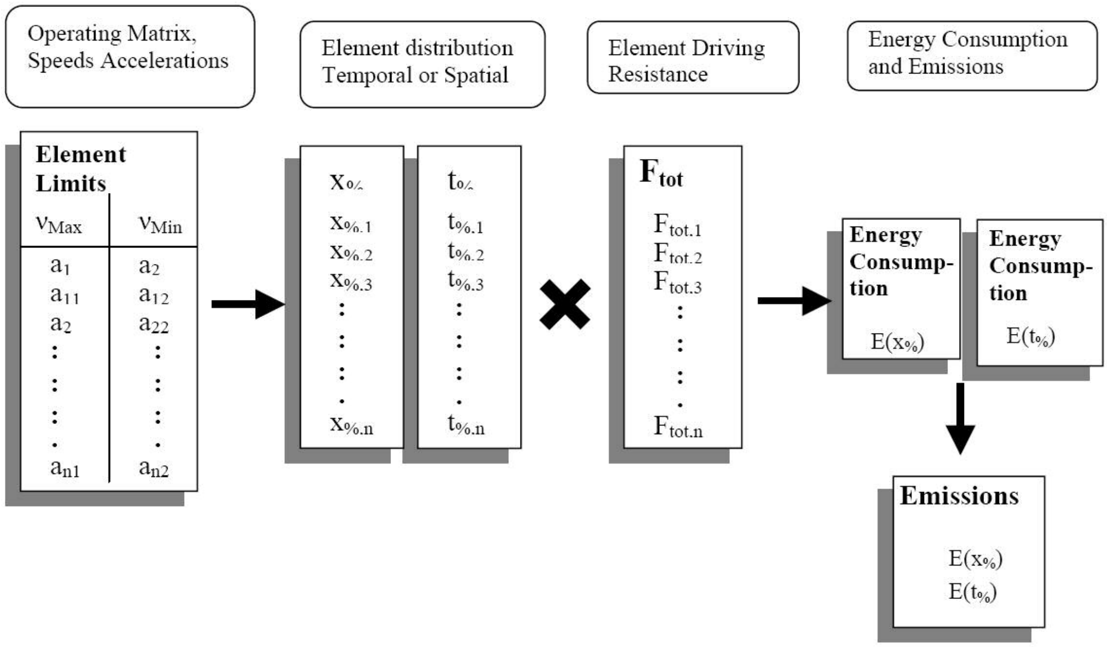

Figure C-1: The basic principles of the rail emission and energy consumption model.

To improve accuracy, gradient resistance should also be included. Since both acceleration and gradient resistance are proportional to the train mass, gradient resistances can be included in calculations by a correction to either rolling resistance or acceleration resistance. However, detailed gradient information for rail lines is difficult to obtain. Therefore, since it is more likely that elevation differences between cities can be found, gradient corrections will be added for an overall trip.

Ideally, the emissions are a function of each operating condition. That is, they can vary between the operational elements. But in this work, emissions will be calculated from the integrated energy consumption, since reliable data concerning actual emissions for the individual modes are not available. This is only relevant in the case of diesel train emissions, since electricity generation is from entirely different kinds of sources, where there is no connection to the actual operation of the train.

C3.2 Emission calculation method

The energy consumption of a locomotive may be determined from basic scientific principles (*e.g.* the amount of energy required to move a given mass). This type of theoretical approach can be applied to any type of train, regardless of its operation or service. In practice, the energy consumption is a function of gross train weight. However, there are also other parameters that have a significant impact on energy consumption, such as average and maximum speed, aerodynamic characteristics, driving pattern, and the number and frequency of stops. The technological basis of the model is that of driving resistances, and these resistances are shown in **Figure C-2**.

The functional dependencies of the driving resistances are the same for all types of wheeled vehicle (Gillespie, 1992). At steady speed on a flat, straight line there are two kinds of driving resistance that are important:

- Aerodynamic resistance
- Rolling resistance

In reality, conditions may be somewhat different. Gradients give rise to extra resistance due to gravitational attraction, and curves cause extra friction between the wheels and the rails. Hence, the two extra resistances are:

- Gradient resistance
- Curve resistance

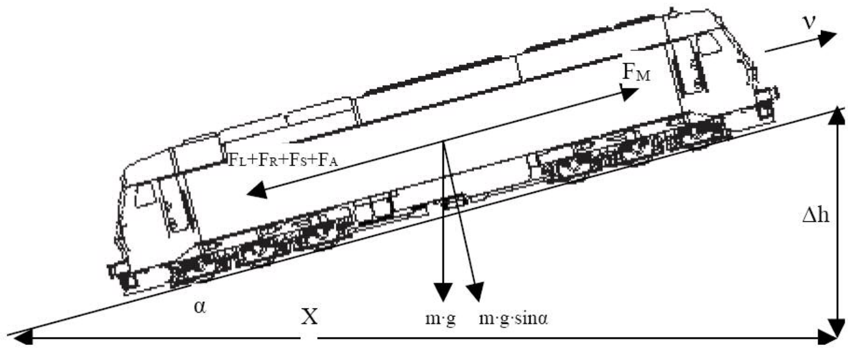

Figure C-2: Representation of driving resistances used in the rail emission and energy consumption model.

The calculation of curve resistance requires detailed information on track layout. Since this information is rarely available, curve resistance is given no further consideration in the model.

Aerodynamic resistance and rolling resistance are dependent upon a range of factors. The techniques for calculating these factors, and their relative importance for a variety of train types, are described by Lindgreen and Sorenson (2005). The basic principles are reviewed below.

Aerodynamic resistance

The aerodynamic resistance is dependent on the frontal area of the train, its shape, and its speed. In addition, atmospheric factors such as air density and wind direction have an effect:

$$F_{air} = 0.5 \cdot C_a \cdot A_f \cdot \rho_o \cdot V^2 \quad \text{(Equation C-1)}$$

where:

F_{air} = the aerodynamic resistance in N.
C_a = the air resistance (drag) coefficient.
A_f = the effective frontal area of the train in m^2, often assumed to be 10 m^2
ρ_o = the air density in kg/m^3
V = the relative velocity between the train and the wind in the direction of travel in m/s

Rolling resistance

The rolling resistance is a function of the total mass of the train and the rolling resistance coefficient:

$$F_r = f_r m \cdot g \quad \text{(Equation C-2)}$$

where:

F_r = the rolling resistance in N.
f_r = the rolling resistance coefficient.
m = the total mass of the train in kg.
g = the acceleration of gravity (9.82 m/s^2).

The above resistances are accompanied by any motion of the train, and are used for steady-state calculations on flat routes. In actual operation the conditions may be somewhat different. Gradients give rise to extra resistance due to gravitational attraction, causing the extra resistance.

Gradient resistance

The gradient resistance is dependent on the weight of the train and the size of the gradient to which the train is exposed.

$$F_g = m \cdot g \cdot \sin(\alpha) \quad \text{(Equation C-3)}$$

where:

Fg = the gradient resistance in N.
m = the total mass of the train.
g = the acceleration of gravity.
α = angle of the slope through which the train is travelling.

In the calculation of an operating pattern from point to point, it is not necessary to calculate the gradient resistance for each individual grade. In general, it is sufficient to calculate the height difference at the origin and destination, and to apply this value to the total route. This gives the net gradient resistance. It is assumed that the extra power the train uses to force a grade is returned when the train goes downhill.

Acceleration resistance

The final resistance to be considered is that due to acceleration of the train.

$$F_{acc} = m \cdot a \quad \text{(Equation C-4)}$$

where:

F_{acc} = the acceleration resistance in N.
m = the total mass of the train.
g = the acceleration of gravity.
a = the acceleration in m/s^2.

Curve resistance is not normally important. It is one of the smallest driving resistances, and since it is very complicated to calculate and requires very detailed route information, it is excluded from further consideration (Friis Hansen, 1991).

Of these resistances, the rolling and aerodynamic resistant are dependent on equipment design, and vary from train to train. The acceleration and gradient resistances are only dependent on the total mass of the train. Methods for the estimation of these parameters are available in the literature (*e.g.* Mehlhorn, 1995). In addition, reasonable estimates can be made if so-called coast-down data are available (*i.e.* the speed-time history for a flat section of track with no braking).

It is generally much more complicated to calculate driving resistance for goods trains, since they typically have an inhomogeneous composition, and vary greatly in form and appearance (in contrast to a passenger train, for example). In many cases, goods trains are composed of many different wagon types, each having its own resistance values and frontal area. For a comprehensive explanation, see Lindgreen and Sorenson (2005a).

Given an operating condition, the energy consumption rate for moving a train is:

$$\dot{E}_{tr} = (F_{acc} + F_g + F_r + F_a) \cdot V \quad \text{(Equation C-5)}$$

This can be considered to represent the energy delivered at the wheels, which must be produced by a prime mover, either a diesel engine or an electrical power generation unit. The primary energy consumption is:

$$\dot{E}_{pri} = E_{tr} / \eta_{pri} \quad \text{(Equation C-6)}$$

Given a speed and acceleration, it is possible to calculate the energy consumption for a given driving condition. Average speed and accelerations within a matrix element are used. By dividing the operation into a matrix of speeds and accelerations, it is possible to calculate the energy consumption and emissions for any driving cycle by summing up the energy consumption for the individual conditions, weighted by the frequency:

$$E_{tot} = \sum_{i=1}^{N_{MODE}} \dot{E}_i(t) \cdot f_i(t) = \sum_{i=1}^{N_{MODE}} \dot{E}_i(x) \cdot f_i(x) \quad \text{(Equation C-7)}$$

Figure C-3 shows the speed-time history of an inter-city train, and the resulting speed-acceleration distribution. The description of the driving behaviour can be made on a second-by-second basis, but if driving modes are assumed to be independent, then the only requirement is a corresponding distribution matrix of operating conditions. That is, the sequence of operations is assumed not to be important, only their frequency.

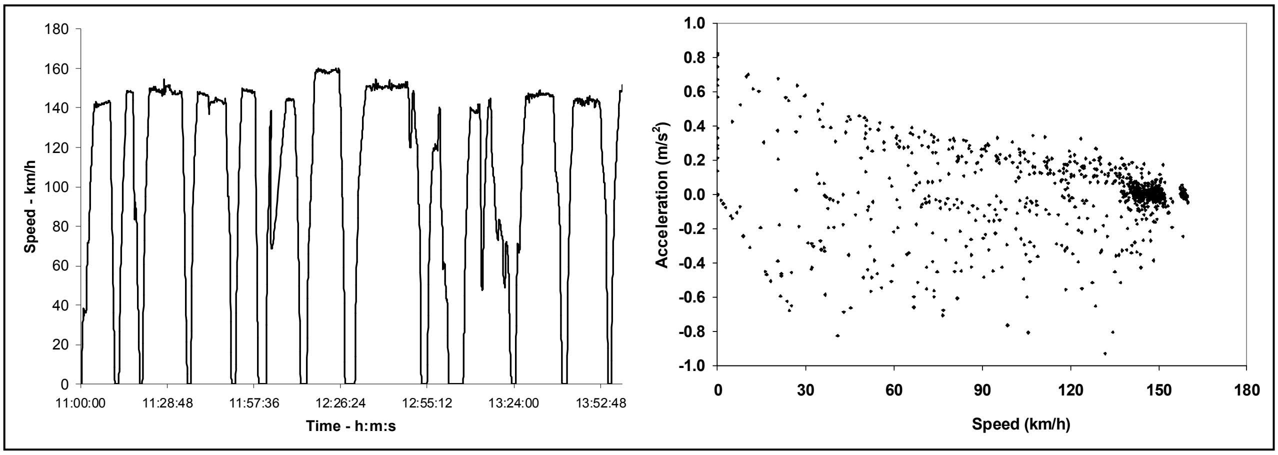

Figure C-3: A driving pattern for a Danish inter-city train (left) and the acceleration as a function of the train speed (right).

It is also possible to construct distributions on a spatial basis, in other words the percentage of the total distance which is driven at a given speed and acceleration. This approach can be advantageous where times and distances can be obtained from a timetable. **Figure C-4** shows the spatial and temporal distributions for regional train operation. A disadvantage of the spatial distribution approach is the treatment of the time when the train is stationary. No distance is covered, yet some energy is consumed, and emissions produced. In order to evaluate this, some experimental data were examined for the regional train shown in **Figure C-4**. The experimental data relating to the relative amounts of time and distance spent in different operational modes (‘controller steps’) for the locomotive-hauled train. The emissions during the individual controller steps were known and used to calculate the relative contributions of the different phases of operation.

Table C-1 shows the energy consumption and emissions for the different operation steps. The load collective shows that over half of the driving time occurs at idle. It can be seen that for the fuel consumption, CO_2, NO_x and particle emissions, idle operation is responsible for only about 5%. For HC and CO idle produces about 22% and 13% of these emissions respectively. That is, large portions of the HC and CO emissions occur at idle, and also at full load (step 8). Operation at full load accounts for about 30% of the total operation time. It is here that the main part of the energy consumption and emissions are found. For the fuel consumption, CO_2, NO_x and CO about 75% of the consumption/emissions occurs at full load. The shares of the different operating steps for the total operation are typical for locomotive-hauled regional trains. For international trains the conditions are different. The share at full load is nearly the same, but the relative amount of idle operation is significantly reduced, which is due to the reduced number of stops per km.

This indicates that for modelling purposes, the use of a spatial distribution is a suitable alternative to the temporal distribution. This means that timetable information can be used to obtain reasonable descriptions of train operation for the purpose of modelling energy consumption and emissions. In the modelling work, basic operating pattern frequency distributions have been developed for a number of train types (primarily Danish), but only for small gradients. It is straightforward to change to other types of operation, provided one has access to driving patterns for the type train concerned. This approach can be used for a single train on a single line, or for a given type of train and a national or international network. For comparison, it is advantageous to use the same basic model for different scales. This reduces potential bias from different modelling approaches. Changes in technology can easily be incorporated in a physically correct manner. Train weight is one obvious parameter, but changes in rolling and aerodynamic resistances can also be applied.

It is necessary to select a size for the matrix elements (*i.e.* the resolution of speeds and acceleration). A regional train was selected for evaluation because of the large range of speeds and accelerations in its operation. The distribution for a single operation is shown in **Figure C-5** for the regional train whose distributions were shown in **Figure C-4**. The speeds were divided into 2, 3, 5, 10, 15 and 25 intervals, and calculations performed with 10 acceleration intervals. The accelerations were then divided into 2, 4, 5, 10 and 20 intervals and calculations were performed with 15 speed intervals. The effect of matrix resolution is shown in Figure 3, which shows that above 10 acceleration intervals and about 5 speed intervals the results are not dependent on matrix resolution. There was little difference in the results, whether calculated on a temporal or spatial distribution. The low sensitivity of the speed interval is probably due to the train being a regional one, and even though there are many speed levels, energy consumption is dominated by that used for the accelerations. In general, it is recommended that at least 15 speed intervals and 10 acceleration intervals be used.

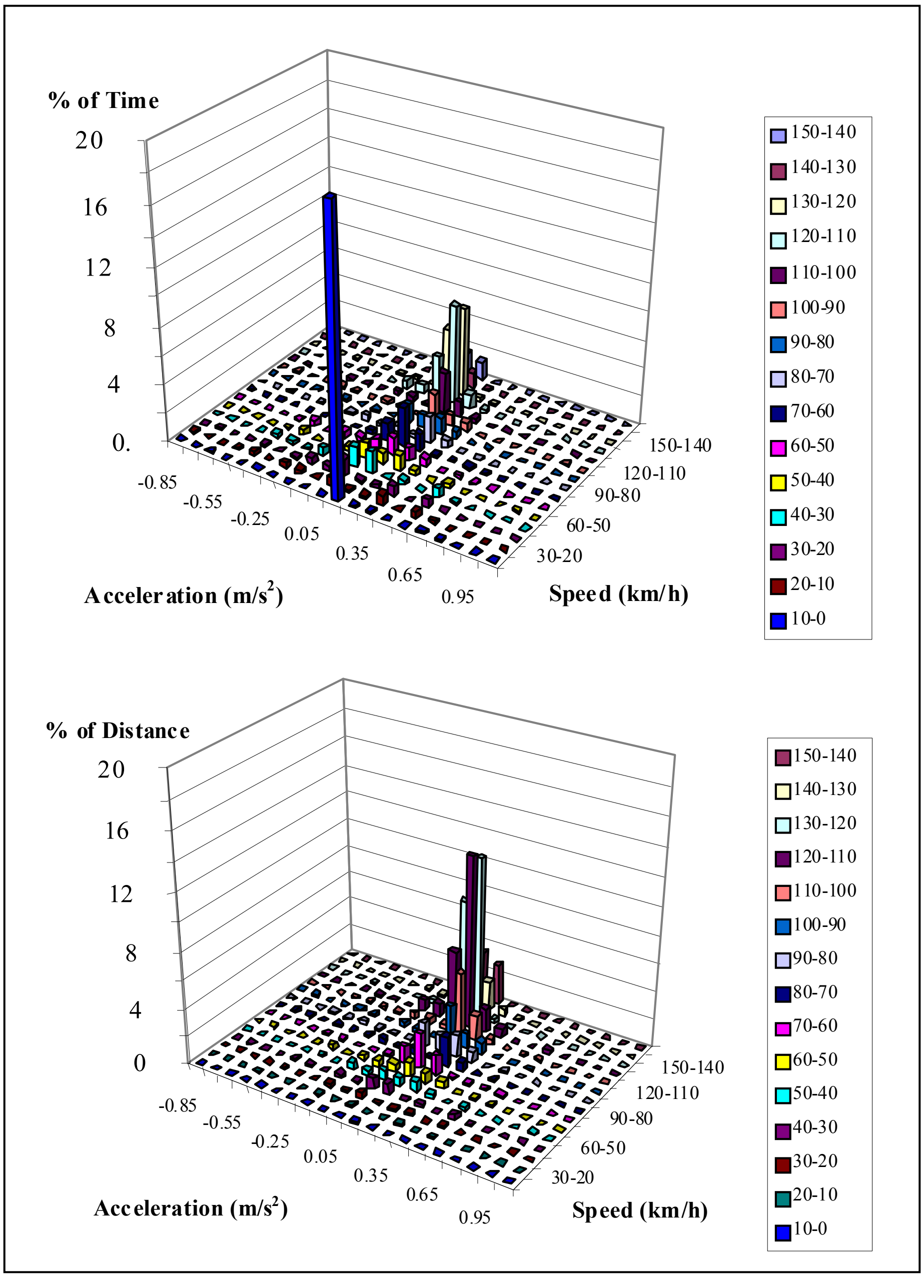

Figure C-4: Temporal and spatial distributions of operating conditions for a Danish regional train.

Table C-1: Percentage load collective for the MR train.

Controller step	Time (%)	Distance (%)	Fuel consumption (%)	CO_2 (%)	NO_x (%)	HC (%)	CO (%)	Particles (%)
0	51	34	4.94	4.82	5.90	21.93	13.19	5.36
1	2	3	0.27	0.26	0.30	0.68	0.32	0.19
2	3	4	0.95	0.91	0.76	1.23	0.71	0.89
3	2	3	1.47	1.42	1.37	1.35	0.61	1.59
4	8	12	7.54	7.43	7.36	5.89	2.52	9.26
5	3	4	3.34	3.28	2.95	2.48	1.54	4.88
6	2	3	3.49	3.47	3.03	2.42	2.83	4.23
7	2	2	4.49	4.52	4.51	3.27	4.26	4.88
8	28	35	73.50	73.89	73.83	60.74	74.04	68.72
I alt	101	100	100.00	100.00	100.00	100.00	100.00	100.00

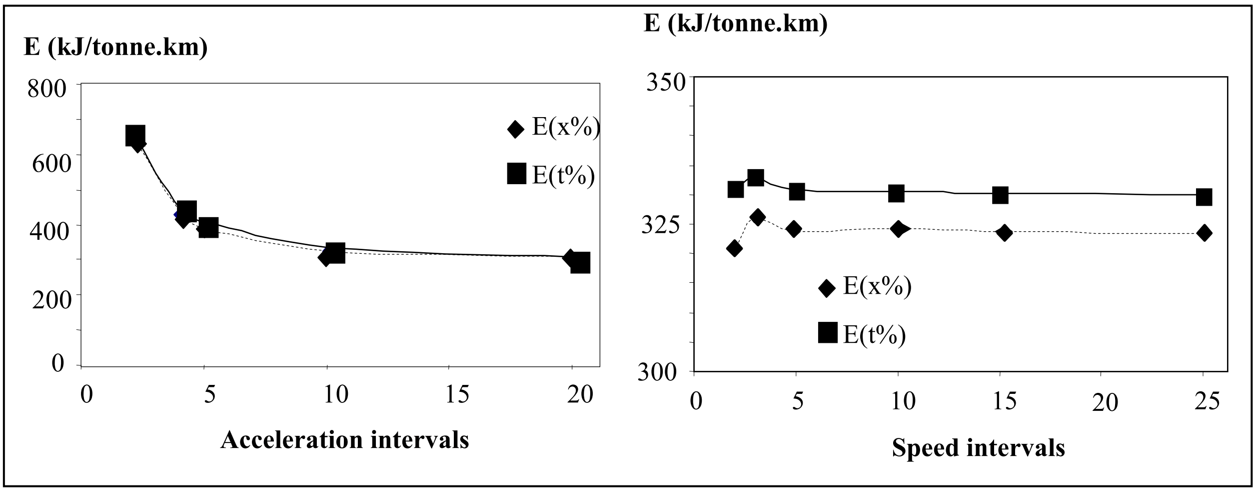

Figure C-5: Effect of matrix resolution on the calculated energy consumption of a regional train. The units of the energy consumption (**E**) are kJ/ton-km.

C3.3 Auxiliary energy consumption

Passenger trains in particular have other sources of energy consumption than propulsion. These include the heating and cooling loads, and electrical power to operate lights, instruments and other electrical accessories. **Figure C-6** gives an example of the heating losses associated with the operation of a passenger train during a one-year period.

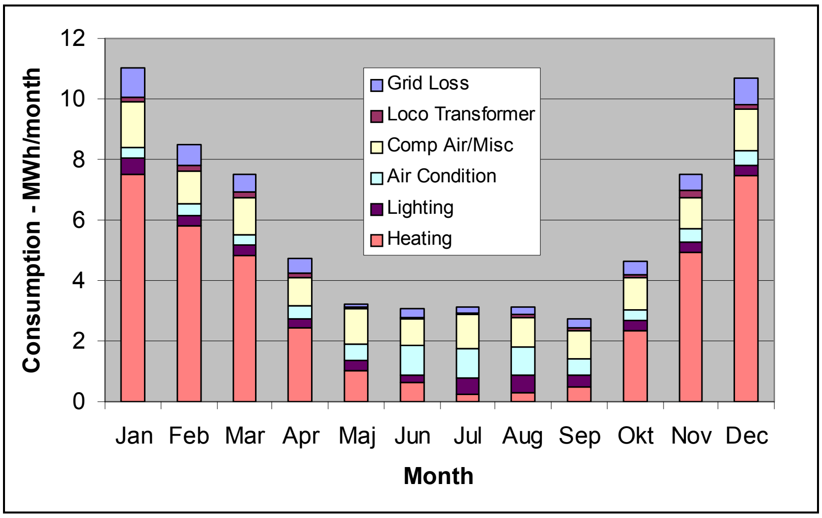

Figure C-6: The amount and distribution of energy consumed by a passenger train during a year.

The heating power varies significantly throughout the year, and the results can be used to provide an order of magnitude estimate of auxiliary energy consumption. The results indicate the relative consumption for auxiliary power is fairly low, and is comparable to the uncertainties in the basic energy consumption and emissions of passenger trains. Therefore, it was not incorporated into the model specifically, although information is provided to allow its importance to be estimated. The systematic determination of these losses, their relation to train size, operating conditions, and local weather conditions represents a potential research project of substantial size.

C3.4 Classification of vehicles and operational modes

In the model presented, five types of train have been included:

- High-speed passenger train
- Inter-city passenger train
- Regional passenger train
- Urban passenger train

- Goods train

It was intended that a wider variety of trains would be included, but the relevant information could not be obtained. The train types included are felt to be representative of a wide spectrum of European trains. The model is presented in an open fashion, and the user manual explains the procedures involved in expanding the model, changing the basic technological parameters, and adding new classes of train. The purpose of this is to use a common modelling procedure, and relate changes to known operational or technological parameters, in order to maintain a good basis for comparison. The report on technological factors is intended to assist in this (Lindgreen and Sorenson, 2005).

C3.5 Traffic data

In combination with the work on the TRENDS project for EUROSTAT, traffic data were collected and estimated for European rail traffic since the year 1970. In addition, projections have been made for the development in European rail passenger and goods traffic forward to the year 2020. These data and predictions have been included in the model, and emissions calculations can be performed for past years. This can be useful when comparing the predictions of the present model with earlier models, or calculation methods. The methodology used for establishing these values is presented in the TRENDS report (Georgakaki *et al.*, 2002).

C4 Model Validation

In order to check the validity of the model, calculations were performed to compare calculated and experimental values of energy consumption and emissions. Three types of calculation were made: (i) a detailed second-by-second calculation of the driving pattern of a train, (ii) a matrix-based approach using the temporal distribution, and (iii) a matrix-based approach using the spatial distribution. Experimental results were obtained from a power collective and operating-mode-dependent emissions factors. The emission factors were known for the different controller steps, and the emissions could be calculated using these data and the operational data for the route (*i.e.* the amount of time the train spent in each controller step).Data were only available for diesel trains. In principle, the energy consumption at the wheels required to move a train is independent of the propulsion type (Georgakaki *et al.*, 2002). For the calculations, average fuel-based emissions factors were applied to the energy consumption (Jørgensen and Sorenson, 1997).

The energy consumption for three different types of locomotive-hauled trains are shown in **Figure C-7**: diesel hydraulic local/regional trains, diesel-electric regional trains, and diesel-electric goods trains, including both general freight and postal trains. The trains operate at different times and over different routes. In general, the simulation results agree with the results from controller data and from a detailed, second-by-second simulation. The spatial and temporal distributions gave similar results, and all of the methods followed the same general trend for differences between the individual runs. Energy consumption is fundamental, and a good prediction of energy consumption is needed to have confidence in emissions predictions. It can be said that the modelling methodology gives an acceptable prediction of both the level and operating trends in energy consumption for different kinds of train. These results are interpreted as a basic confirmation of the modelling principle.

A second comparison is shown for NO_x emissions, one of the most important air pollutants for trains. Results for the same trains as **Figure C-7** are shown in **Figure C-8**. Because an average, fuel based NO_x emission factor is used, the results show similar trends as those for fuel consumption. The comparison with the results from the operating collective and the known engine emissions factors indicates that with current diesel engine technology, the use of average fuel based emissions factors for NO_x emissions is acceptable. Other pollutants are more sensitive to the engine operating conditions, and the predictive capability of average fuel-based emissions factors is not expected to be as good. Due to significant variations from engine to engine, and between operating points for an individual engine, a very detailed model and large database would be needed to make a more technically accurate emissions model. On almost any scale one could consider, a significant amount of averaging would be needed for the emissions of CO, HC and PM. The use of average fuel-based emissions factors can be said to be the most elementary averaging method.

To obtain a more complete picture of the predictive capability of the model with respect to all pollutants over a wider range than **Figure C-7** and **Figure C-8**, comparisons are shown in **Table C-2** for energy consumption and exhaust gas emissions for three different types of train. Average powertrain efficiencies have been applied for the locomotives. The first row shows that the energy consumption is predicted to within 15%, no matter which simulation method is used. Similar results are obtained for CO_2 emissions, as expected, and NO_x emissions. Particularly for CO_2 the use of an average fuel specific factor is acceptable, but this approach also works well for NO_x.

The other pollutants are known to be more sensitive to operating conditions, and **Table C-2** shows that the variations of the predictions for these pollutants are larger than those for energy consumption, CO_2 and NO_x emissions. The poorest agreement was obtained for HC emissions, which are known to be particularly engine-sensitive. Whilst it may be tempting to consider mode-dependent emissions factors for CO, HC and PM in the matrix approach, it must be realised that these pollutants are sensitive to specific engine types, and also to the individual adjustment and condition of each engine within an engine type. An extensive database would be necessary in this case, and there would still be a large degree of variation, as there is in the case of emissions from road vehicles.

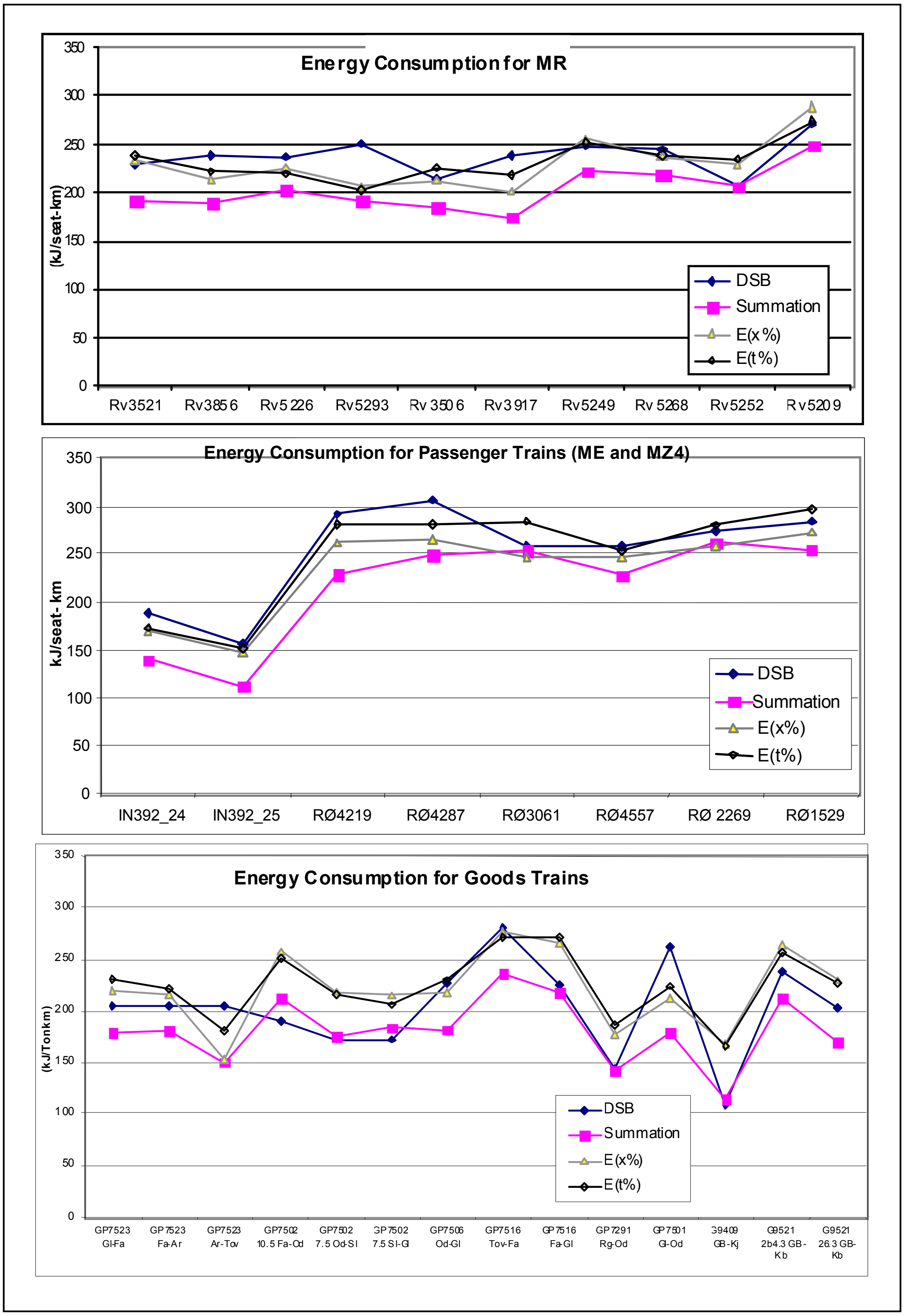

Figure C-7: Comparison of energy consumption for three kinds of locomotive-hauled diesel trains. Experimental results = 'DSB'. Calculations from a detailed train simulation = 'summation', and from spatial - 'E(x%)' and temporal 'E(t%)' distributions of operating patterns.

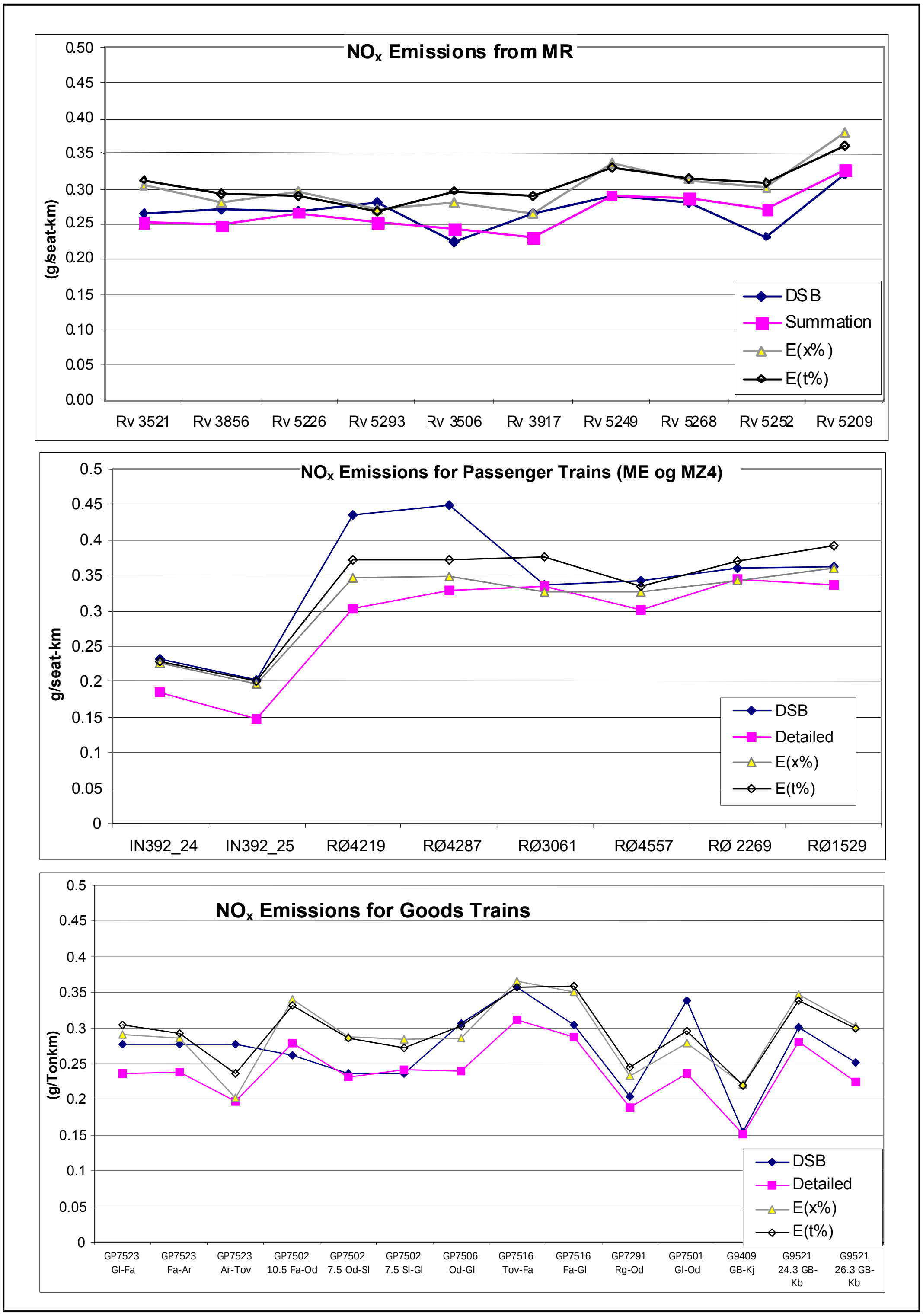

Figure C-8: Comparison of NO_x emissions for three kinds of locomotive-hauled diesel trains. Experimental results - 'DSB'. Calculations from a detailed train simulation - 'summation', and from spatial - 'E(x%)' and temporal 'E(t%)' distributions of operating patterns.

Table C-2: Comparison of average relative energy consumption and emissions predicted by a detailed (second-by-second) calculation and by matrix calculations based on spatial and temporal distributions of operating conditions. Values indicated are relative to those from an operating collective using mode-specific fuel consumption and emissions factors.

Emission	Motor coach			Loco power passenger			Goods		
	Detail	E(x)	E(t)	Detail	E(x)	E(t)	Detail	E(x)	E(t)
Energy	0.85	0.97	0.98	0.85	0.93	0.99	0.91	1.11	1.13
CO_2	0.90	1.02	1.03	0.84	0.92	0.98	0.98	1.20	1.22
CO	0.73	0.83	0.84	1.11	1.23	1.31	1.25	1.54	1.56
NO_x	0.99	1.13	1.15	0.84	0.92	0.98	0.90	1.10	1.12
HC	0.38	0.43	0.43	1.26	1.40	1.48	1.22	1.50	1.52
PM	0.97	1.11	1.12	1.51	1.66	1.76	1.41	1.73	1.76

The model can be applied either to a time distribution or a spatial distribution of operating modes. The energy consumption matrix is based on the percentage in each acceleration-speed block in relation to the total operational pattern. The calculation of energy consumption is based on the use of physical parameters for determining train energy needs (rolling resistance, aerodynamic resistance, and acceleration).

C5 Summary and conclusions

A model has been constructed for estimating energy consumption and emissions from rail traffic. Calculations can be made on the basis of knowledge of a distribution of operational characteristics with respect to either time or distance. The model has been evaluated on 18 passenger train routes and 12 goods train routes. The results were compared with energy consumption and emissions calculated on the basis of a measured operation collective for engine power, and measured engine energy consumption and emissions.

For the passenger trains, the model was able to calculate energy consumption within 15%. For goods trains, the variation was slightly higher. NO_x emissions could be estimated to a similar level of accuracy using average emissions factors applied to the total energy consumption, and not to the individual operation points. Emissions of CO, HC and particulate matter were more sensitive to individual operation conditions and specific engines, and could be estimated to within 25-30 % using average emissions factors.

In conclusion, the concept of dividing operating patterns into a speed-acceleration matrix and - calculating energy consumption from train data and rolling resistance parameters - is viable. The emission calculation method includes technical factors in a correct, but not overly complicated manner. It is possible to apply the model to a wide range of fleets, from a single run to a national average for a train type. The main requirement is that a reasonable estimate of the temporal or spatial distribution of the operating conditions for the type of train is known.

One possibility for obtaining data is the use of timetables. In this case, distances are either known or readily available, and travel times are given directly. With standard corrections for acceleration/deceleration times or distances, operating statistics are readily available for almost any passenger route for schedule traffic. Goods traffic travel data is not generally available in this form.

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PART D: INLAND SHIPPING

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D1 Background

This Part of the Report presents the work conducted in ARTEMIS on emissions from inland shipping. More detailed information can be obtained from the report by Georgakaki and Sorensen (2004).

The congestion of Europe's road and air routes, and the expansion of trade within the EU, have led to increased interest in the utilisation of potential alternative transport modes, in particular inland shipping. Inland shipping can serve regions which are inaccessible by sea transport, and thus relieve some of the pressures on the road and railway networks. However, inland shipping is, for the most part, unregulated in terms or air pollutant emissions, and the regulations proposed in recent years by the Central Commission for the Navigation of the Rhine and the United Nations Economic Commission for Europe (UNECE, 2000) will not show any effects for some time on account of the slow replacement rate of engines in the sector. Inland shipping is therefore emerging as a significant source of pollution. The claim that off-road transport is both economical and environmentally friendly has come under scrutiny as the effect of modal shift are examined. Whilst economies of scale give these modes an advantage, the specific route, the vehicle used, the actual load and the need for further transhipment may make a difference in terms of the overall benefits of modal shifts. This is especially relevant when such changes are considered for short distances and have impacts on a local scale.

Western Europe has a waterway network which has a length of approximately 25,000 km and transports an estimated 100 billion tonne-kilometres of goods every year (Georgakaki and Sorensen, 2004). It is claimed that the inland waterways of Europe have a vast unused capacity. Except for the Rhine, which carries traffic to up to 80% of its available capacity, other waterways are estimated to only carry up to 50% of their theoretical capacity (Pflieg, 2002). Until recently, strategic developments have assigned a low priority to inland navigation, but this has recently changed with the recognition of the potential for the development of inland waterways and the areas surrounding them.

As far as the modelling of fuel consumption and emissions is concerned, in the MEET project the emphasis was almost entirely on marine shipping, and inland shipping was treated by analogy with general cargo shipping (European Commission, 1999). However, there are several factors which cause the operational characteristics of inland ships to be different from those of their seagoing counterparts. Firstly, they sail at lower speeds and in restricted waterways. The lower speeds reduce energy consumption and emissions, whereas shallower depths increase sailing resistance and hence fuel consumption and emissions. In order to make the most of the limited space on inland waterways, vessels tend to be squarer in shape than seagoing ships. This also causes the sailing resistance to differ from that of seagoing ships. The effects of these factors needed to determined in more detail in ARTEMIS.

An emission model for inland shipping was also developed as part of the TRENDS[42] project. The purpose of TRENDS was to develop a system for calculating a range of environmental 'pressures' due to transport. These environmental pressures included emissions and energy consumption from the four main transport modes - road transport, rail transport, shipping and air transport. The system was constructed to enable a simple scenario analysis, including vehicle fleet dynamics (such as turnover and evolution), for the EU15 member states. The final aim of the study was to produce a range of transparent, consistent and comparable environmental pressure indicators for the various modes of transport. These were calculated directly from the activity levels, and reflected the potential changes in the state of the environment, or risk of specific environmental impacts which any changes in policy would have.

ARTEMIS aimed to provide a better understanding of the factors influencing vessel operation on inland waterways, building upon the work in MEET and TRENDS. The main objectives of the ARTEMIS work on inland shipping were:

- *To define representative classes of shipping.* The categories had to represent sectors which could be identified from a technical point of view, taking into consideration the availability of relevant traffic data.
- *To select representative vessels and traffic conditions for the shipping classes, and to evaluate the emissions characteristics of the classes of ship.* Once the appropriate classifications had been selected, detailed modelling and/or experimental data were required to obtain the fuel consumption and exhaust emission characteristics, and to define the average emission characteristics of each class of vessel.
- *To construct a model.* The data from the other tasks had to be compiled and evaluated in order to develop relationships between parameters affecting emissions and information that end users could be expected to have at their disposal. The main aim was to develop models which would be open and accessible for future modification, and suitable for use in a database format similar to that being developed in TRENDS.
- *Estimation of future trends.* Since strategic comparisons of transport modes involve systems to be constructed in the future, it was necessary to estimate future developments. Projections of the trends in the important model parameters were therefore required.

D2 ARTEMIS model overview

Most of the previous studies relating to air pollution from inland shipping have assumed average fuel consumption values and emission factors. Whilst this offers an overview of the situation which may well be close to reality, it provides no

[42] TRENDS = TRansport and ENvironment Database System

understanding of how factors such as speed, load and even hull shape and principal dimensions affect emissions. The ARTEMIS project aimed to reduce some of the uncertainty via a more detailed study of inland shipping.

The basis for the ARTEMIS technical model already existed, in the form of a detailed spreadsheet (Georgakaki, 1999). This spreadsheet could be used to calculate the energy consumption and emissions from inland vessels under different service conditions (speed, waterway dimensions, load, *etc*). However, the accuracy of this model had not previously been evaluated, and so the weight of the technical work was shifted to assessing its performance, making improvements where necessary, and adapting the model to the needs of ARTEMIS.

In order to validate the model in ARTEMIS, experimental data were provided by the European Development Centre for Inland and Coastal Navigation (VBD). The validation data covered all the defined vessel classes, in order to ensure model accuracy for the range of vessels examined. Full-scale measurements on vessels in operation and towing-tank tests were supplied, along with information on vessel characteristics and operation. Based on the experimental data, adjustments were made to the model to establish a consistent method for a wide range of vessel types and operating conditions, and to evaluate the accuracy of the model.

A schematic representation of the ARTEMIS modelling process is shown in **Figure D-1**. Nine ship classes were defined, based on a vessel's size and the waterways it could navigate. Typical vessels from the defined classes (and sub-classes) were examined under different service conditions in order to provide a set of indicators describing the emissions behaviour on specific waterways. Since the dimensions of vessels in one class forbade them from operating in waterways defined by the dimensions of the previous class, the matrix of indicators produced is as pictured in **Figure D-1**.

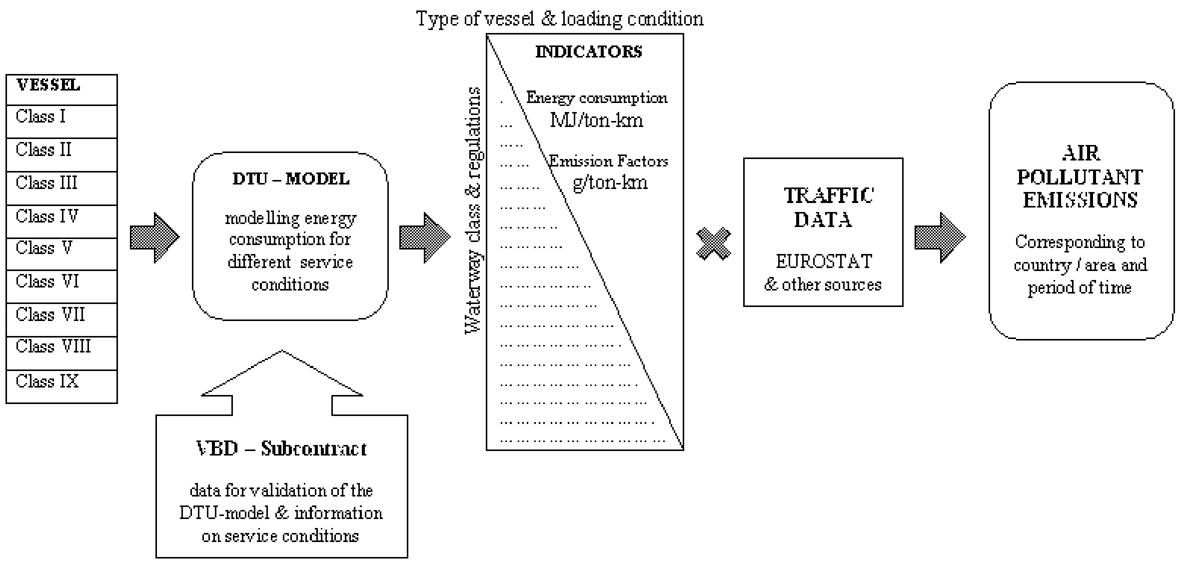

Figure D-1: Schematic presentation of the ARTEMIS modelling process.

The ARTEMIS model had to be able to produce both detailed information on the performance of individual vessels and aggregated results for large parts of the fleet operating in certain areas. That is to say, it had to be applicable over a range of spatial scales, from single ships to international traffic. Ideally, given the necessary traffic data, the estimation of the emissions from inland shipping should be possible for any of geographical area. It should also be possible to compare vessels in terms of their efficiency on different waterways, or perform other kinds of scenario analysis, such as modal shift in cargo transport. However, data which give a better description of the fleet, the traffic and the waterways are needed before this can be achieved.

D3 Classification of inland vessels

The vessel classification system in the ARTEMIS model is based on technical grounds. However, the nature of inland navigation is such that most sources are more or less in agreement on classifications, and there are no major inconsistencies. Furthermore, there has been a great effort to standardise waterways during the last 20 years, and this has effectively resulted in the standardisation of vessel classification.

D3.1 Vessel type and size

Inland vessels are mostly used for the transportation of low-value, bulk goods. Typically, these consist of raw materials and mass products such as animal feed, mineral aggregates, petroleum, and various types of waste (including household refuse). In addition, there is a growing trend towards the use of containers in inland shipping, allowing a wider range of commodities to be transported conveniently. There are classifications based upon the typical freight carried or the designated service purpose (as in shipping registers).

In maritime shipping, vessel type is an important characteristic, since the vessel form, its service speed and other features will vary significantly between, say, open sea tankers and container vessels. However, in inland navigation it is more the waterway than the freight type which imposes restrictions on the form and speed of vessels. Classification with respect to cargo type is considered unnecessary, as inland vessels designed for liquid, solid bulk, or container freight are very similar. The definition of vessel type with respect to cargo does not enter as a factor in the present modelling process, although transport data can be found in terms of the types of goods shipped.

Another common classification scheme for inland vessels is one based on carrying capacity. However, carrying capacity is not sufficiently descriptive in the context of specific waterways and service conditions. Exact dimensions define whether a vessel is qualified to navigate certain waterways, and how effective the service will be. The capacity that may be utilised depends upon the draught restrictions.

One of the key issues to be considered when studying inland ship performance is the type of waterway travelled. European inland waterways are classified according to their regional or international importance, their principal dimensions, and their physical characteristics. Waterway outline, permissible draught, and minimum height under bridges, are some of the factors defining the types of vessel which can travel on the waterway. The design of inland shipping is geared towards the requirements of the waterway along which it is operated, rather than to the country of manufacture. This results in a variety of vessel designs, even within a single country, which are specific to individual waterways.

Small vessels transport only a fraction of the total freight tonnage, but they dominate inland shipping movements in the higher reaches of rivers and within small canal networks. Thus, such vessels become significant to total transport emissions, especially as the average age of these vessels is considerably greater than that of their larger counterparts, and they tend to use relatively old engine technologies that are associated with high energy consumption and emission rates.

Pushed convoys are also common on European rivers. These are very flexible in terms of size and cargo capacity - they can consist of between one and nine barges in various configurations, and can reach a maximum dead-weight capacity of 27,000 tonnes. The standard freight vessel is the so-called 'Europe-II' barge, which has a nominal cargo capacity of 1,600 tonnes at 2.5 m of draught. The two dominant self-propelled vessels, otherwise known as motorships, are often coupled with barges in-line and/or in parallel to form convoys. This is also the case for some of the smaller motorships, which explains why there is a wide variation in the power capacity of vessels that are otherwise similar.

On the lower sections of a number of rivers, maritime vessels, coasters and river-sea vessels are also present within the fleet. These vessels, which typically have a cargo capacity of up to 5,000 tonnes, are particularly important in servicing the lower courses of rivers leading to deep-sea hinterland. River-sea vessels are rarely specialised, and are mostly built as multi-purpose crafts that can transport various types of cargo. These vessels are used as an integrated method of transport, combining short-sea journeys with inland waterway transport, thus minimising effort and cost since transhipment is avoided. Due to the effect of the waterway condition on a ship's performance, and also the fact that spatial reference is of interest for the practical use of the ARTEMIS project, inland ships were classified according to the type of waterway they are allowed to navigate. The classification selected for ARTEMIS is given in **Table D-1**, and a schematic outline is shown in **Figure D-2**. Classes I to III refer mostly to self-propelled inland vessels, classes IV and V include both motorships and pushed convoys, and classes VI to IX represent pushed convoys, river-sea vessels, and maritime vessels that operate in the lower parts of rivers. The difference between inland vessels, river-sea vessels or different convoy configurations can be given as an additional field, as mentioned above, resulting in sub-classes of the type 'Class VIII – R/S' and 'Class VIII – Convoy 2x2'.

Table D-1: Inland waterway vessel classification in ARTEMIS.

Class	Motorship and Pushed Convoy characteristics					
	Maximum length (m)	Maximum beam (m)	Draught (m)	Tonnage (tonnes)	Waterway class	Minimum height under bridges (m)
Class I	38.5 – 41	4.7 – 5.05	1.4 – 2.20	180 – 400	I	3.0 – 4.0
Class II	50 – 57	6.6 – 9 .0	1.6 – 2.5	400 – 650	II	3.0 – 5.0
Class III	67 – 80	8.2 – 9.0	1.6 – 2.5	470 – 1,000	III	4.0 – 5.0
Class IV	80 – 85	9.5	2.5 – 2.8	1,000 – 1,500	IV	5.25 – 7.0
Class V	95 – 110	11.4	2.5 – 4.5	1,500 – 3,000	Va	5.25 – 9.10
Class VI	172 –185	11.4	2.5 – 4.5	3,200 – 6,000	Vb	5.25 – 9.10
Class VII	95 – 110	22.8	2.5 – 4.5	3,200 – 6,000	VIa	7.0 – 9.10
Class VIII	140 – 195	15 – 22.8	2.5 – 4.5	6,400 – 12,000	VIb	7.0 – 9.10
Class IX	195 – 285	22.8 – 34.2	2.5 – 4.5	9,600 –27,000	VIc , VIII	9.10

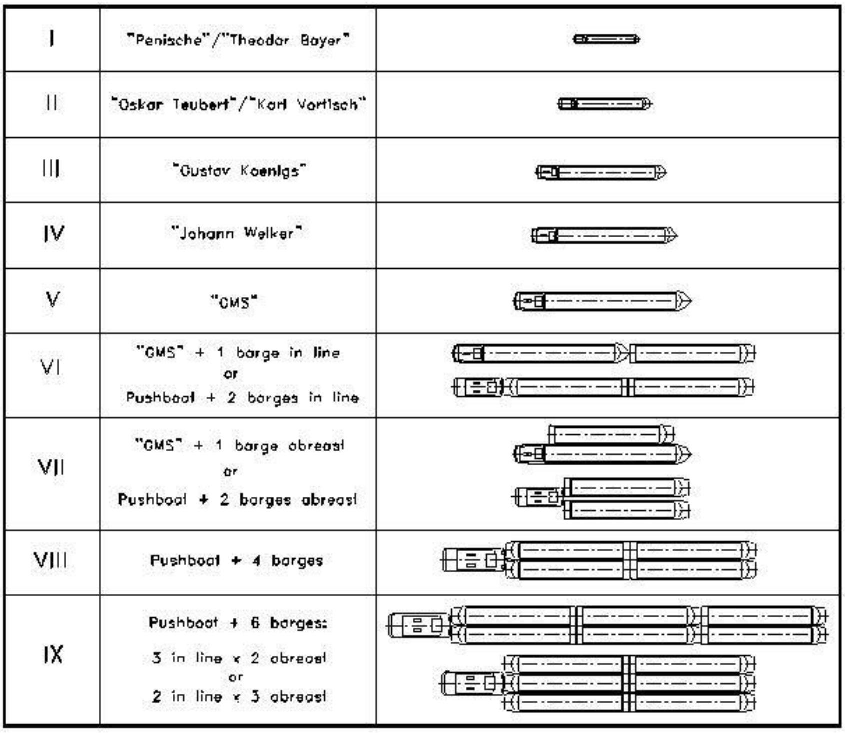

Figure D-2: Schematic overview of inland vessels in the different classes defined for ARTEMIS.

D3.2 Engine type and age

The majority of inland vessels are equipped with medium-speed diesel engines, with the power being transmitted through a gearbox, in contrast to typical sea-going vessels which are generally equipped with low-speed diesel engines coupled directly to the propeller. A number of high-speed engines are also present within the fleet.

The large development of inland shipping during the 1960s has resulted in the present inland fleet being considerably older than its equivalent maritime counterpart. Almost half of the vessels in current service were launched before 1970, with some even as early as the 1930s. Commercial engines of the type and size used for inland vessels have exceptional life spans, and can still be in service after 40 years. Engines used in inland vessels have an average life expectancy of 38 years, with a 50-year maximum. A method was developed to describe the operation of engines of the size and type used in inland navigation to a satisfactory degree for the purposes of the ARTEMIS project.

D4 Model description

The aim of ARTEMIS was to construct a basic model which required the minimum possible input data, which would provide an approximation of a vessel's emission behaviour under cruising conditions. There are numerous methods used in the field of ship design to calculate the power required to propel a vessel under different service conditions, taking into account the influence of all the parameters involved. The problem in using these methods for the purpose of emissions research is that they are designed for the detailed prediction of the performance of a particular vessel, and therefore their use demands knowledge of ship design and information that is generally not available, or even familiar, to researchers in other fields.

The basis for the ARTEMIS work was a model previously developed by DTU (Georgakaki, 1999), which itself extended a method originally presented for the calculation of ship resistance for sea-going vessels (Guldhammer and Harvald, 1965,1974). Modifications to account for the specific operation of inland vessels were made using data from relevant sources, based on the criterion of easy computation and application to limited input data. Through the resistance calculation, the necessary power requirement, and therefore energy consumption of the engine was estimated, leading to the calculation of air pollutant emissions based on fuel-specific emission factors. The main aspects of the ARTEMIS model are presented in the following Sections.

D4.1 Input data

Although the aim was to create a model for non-expert users which kept the input data requirements to a minimum, for many of the model parameters which are essential to the calculation values may not be readily available to the user. In such cases, algorithms have been introduced to estimate default values. This inevitably has some impact on the overall accuracy of the calculation. For some of the input parameters an effort was made to estimate the loss in accuracy, but this was not possible for all parameters due to the lack of validation data. The definitions and significance of input parameters are discussed in the report by Georgakaki and Sorensen (2004).

The input required for the model calculation is restricted to the following parameters:

- Vessel length
- Vessel breadth
- Vessel draught (at a specified load)
- Fraction of load draught for calculation
- Speed relative to water
- Number of propellers
- Waterway depth
- Waterway width

When supplied with these values, the model will calculate all the necessary parameters to perform the resistance calculation, based on an algorithm that approximates missing data by using default values and calculation methods specific to inland vessels. The resistance is then used to determine the engine power and emissions.

The user can also offer the following as input for the design or reference draught:

- Deadweight of vessel for design/reference draught
- Displacement of vessel for design/reference draught
- Block coefficient for design/reference draught
- Actual deadweight for calculation draught
- Actual load (weight of goods)
- Rated power of main engine
- Rated power of auxiliary engine
- Load of auxiliary engine
- Specific fuel consumption of main engine
- Propeller diameter
- Propeller speed (rpm)
- Open water propeller efficiency
- Shaft efficiency
- Overall propulsive efficiency
- Thrust and torque coefficients for propeller

D4.2 Resistance modelling

For the purpose of this project, which calls for a simple and comprehensive way to calculate the power needed to move a vessel through water, the Froude Hypothesis is used, according to which:

$$R_T = R_F + R_R \quad \text{(Equation D-1)}$$

where:

$$R_T = 0.5 \cdot C_T \cdot \rho \cdot S \cdot V^2 \quad \text{total resistance}$$

$$R_R = 0.5 \cdot C_R \cdot \rho \cdot S \cdot V^2 \quad \text{residual resistance}$$

$$R_F = 0.5 \cdot C_F \cdot \rho \cdot S \cdot V^2 \quad \text{frictional resistance}$$

C_T, C_R and C_F are the respective specific resistance coefficients for total, residual and frictional resistance, ρ (kg/m^3) the fluid density, S (m^2) the wetted surface of the vessel and V [m/s] the vessel's speed. The Froude number (Fn_h) is defined in terms of the fairway depth (h), the velocity of the vessel (V) and g the acceleration due to gravity.

$$Fn_h = \frac{V}{\sqrt{gh}} \quad \text{(Equation D-2)}$$

A modified method, based on sea-going technology, is used to determine the necessary power requirement. The energy consumption of the engine is then estimated, leading to the calculation of air pollutant emissions based on fuel-specific emission factors. The details of these calculations are given by Georgakaki and Sorensen (2004). Differences between seagoing and inland ships exist, and are corrected for, in the following areas:

- Breadth:draught ratio
- Longitudinal position of centre of buoyancy
- Hull form
- Appendages
- Roughness
- Air and steering resistance
- Waterway restriction (width and depth)
- Convoy resistance
- Service speed

D4.3 Engine characteristics

An important part of the model is the calculation of engine fuel consumption, since emissions are estimated using fuel-specific factors. For typical diesel engines used in the propulsion of inland cargo ships, the power lies in the range of 250 to

1,500 kW, with the average value of specific fuel consumption being between 190 and 230 g/kWh. A model was developed to estimate the specific fuel consumption of typical engines operating on a conventional third-order propeller power curve:

$$\frac{bsfc - 191.25}{191.25} \cdot P_b^{(1/3)} = 5.3775 \cdot P_b^{(-1/3)} + 0.0827 \qquad \text{(Equation D-3)}$$

where:

bsfc = brake-specific fuel consumption (BSFC) (g/kWh)
P_b = brake power (kW)

The correlation is shown in **Figure D-3**. For loads under 20% there is a consistent underestimation of the BSFC that goes up to 13% for the examined data. In this area the influence of engine size and friction is greater and the assumptions made fail to cover the operation of all the engines examined.

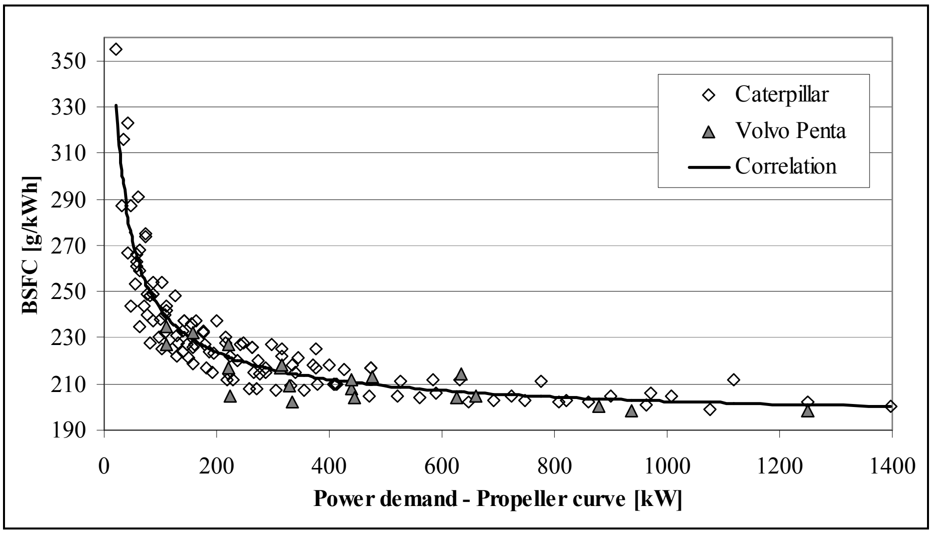

Figure D-3: Agreement of the developed correlation with Caterpillar and Volvo Penta BSFC data.

Based on the above discussion, the developed correlation should approximate the brake-specific fuel consumption adequately for the purposes of ARTEMIS, which deals with cruising conditions. However, if long periods of operation under partial load are expected, estimations based on this correlation will be of reduced accuracy. For older engines, the results are not as good due to the difference in technology.

The power of the auxiliary engines on the different inland vessels typically amounts to approximately 10% of the main engine power. For many of these vessels the auxiliary engine was over 10% of the main engine power, and the relationship between the two engine sizes was found to be dependent on vessel size. Since there was currently only limited information on auxiliary engines, their contribution was taken into account, where appropriate, by assuming a size and load and then adding this as an extra power requirement on the main engine.

Class I vessels only had one engine in the vast majority of cases, but when an auxiliary engine was present its power was, on average, around 50% of the main engine power. Class II and III vessels had auxiliary engines with an average power of 40% of that of the main engine. For class IV the percentage dropped to 30% on average, and for class V to 25%. However, there was a large deviation of power values in all classes. Furthermore, there was no additional information on the usage of the equipment, and therefore assumptions were required concerning the load and time of operation of these engines.

D4.4 Propulsive efficiency

The propulsive efficiency is a very important factor in determining the emissions and energy consumption of inland ships. A value for the overall propulsive efficiency can be estimated based on the propeller open-water efficiency. A relatively simple approach to calculate the propulsive efficiency has been used in the ARTEMIS model. However, the approach requires knowledge of the propeller characteristics and open-water performance. This information is not usually available, and with the uncertainties involved it is doubtful that this extra calculation will add to the overall accuracy over the use of a fixed propeller efficiency. The simulation of propeller performance is difficult to achieve using limited data, especially for operating conditions which are not ideal. The overall propulsive efficiency of a long-range push boat with a six-barge train in a three-abreast/two-in-line formation as a function of speed is given in **Figure D-4**.

The values in **Figure D-4** relate to operation in a relatively unrestricted waterway, and appear to be quite high. Other sources indicate propulsive efficiencies of between 0.2 and 0.4. The reason why propulsive efficiency is surrounded by such uncertainty is the complex propeller-hull interaction, especially at varying water depths where it is subject to dynamic changes. The hull form, the propeller design, the vessel draught, the waterway depth and width, the current speed and direction, the orientation of rudders and number and formation of pushed barges are some of the influencing parameters which can be identified, with the relationship between each parameter and propulsive efficiency being unclear in many cases. The complexity and variety of propulsive arrangements developed to operate under adverse conditions, whilst maintaining acceptable efficiency, also contributes to the increased difficulty of modelling this parameter. For the time being, it is recommended that constant values (within the practical limits stated by VBD) are used for calculations, bearing in mind the likely influence of restricted waterways in reducing the propulsive efficiency (VBD, 2002). As this is reported to be in the range of 0.45 to 0.55 for cruising conditions, a value of 0.5 is assumed for the emission calculations.

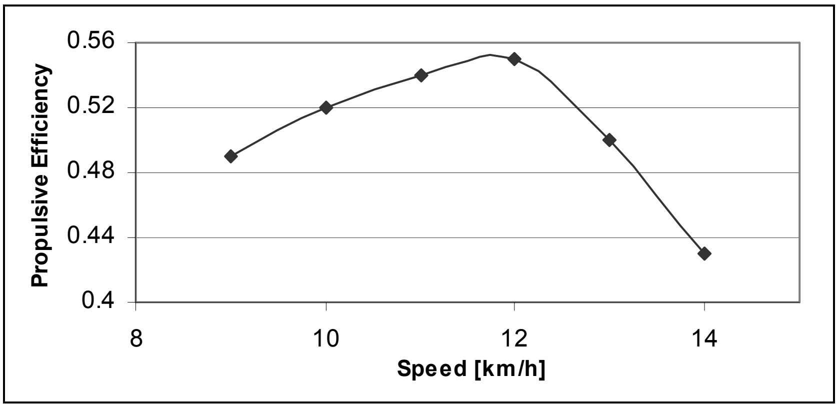

Figure D-4: Typical propulsive efficiency for a long range push boat with 4-6 barges and 2.5 draught operating in a 5 m-deep waterway.

D4.5 Pollutant emissions

The pollutants considered in the model are CO, CO_2, VOC, NMVOC, NO_x, SO_x and PM. Emissions are expressed as grammes per tonne of cargo carried and per kilometre travelled, and are calculated based on the resistance calculation and the assumed values for propulsive efficiency and fuel consumption. Values are also given for the emission of each pollutant per vessel-kilometre and per hour. The energy consumption of the vessel in kilojoules per tonne-kilometre is calculated on the basis of the specified reference load.

$$\textbf{Energy consumption [kJ/tonne.km]} = \frac{P_D[\text{kW}] \cdot SFC[\text{g/kWh}] \cdot \textit{Fuel calorific value}[\text{kJ/kg}]}{10^3 \cdot V[\text{km/h}] \cdot \textit{reference load}[\text{tonnes}]} \qquad \text{(Equation D-4)}$$

$$\textbf{Air pollutant emission [g/tonne.km]} = \frac{P_D[\text{kW}] \cdot SFC[\text{g/kWh}] \cdot \textit{emission factor}[\text{g/kg}]}{10^3 \cdot V[\text{km/h}] \cdot \textit{reference load}[\text{tonnes}]} \qquad \text{(Equation D-5)}$$

The emission factors selected for use in the database are shown in **Table D-2**, and can be found in the Dutch STOWA report concerning emissions from ship engines (STOWA, 1998). Lloyd's Register have also included an inland vessel in their research programme, for which the steady state emission factors are also given in **Table D-2**. Another set of emission factors particular to inland vessels and used for modelling of emissions in the Rhine-Westphalia is given by Schulz *et al.* (1999). The emission factors used in the database calculation can be re-defined by the user.

Table D-2: Emission factors for inland vessels in grammes per kilogramme fuel.

Source	Pollutant								
	CH_4	CO	CO_2	HC	N_2O	NMHC	NO_x	PM	SO_x
STOWA (1998)	0.12	3	3,130	3	0.69	2.9	60	4	3.4
Schulz *et al.* (1999)		5.8	3,150	3.4			48	1	3.4
Lloyd's Register (1993)		1.8	3,250	1.9			56		3.4

D5 Model validation

D5.1 Validation data

Validation data were provided by the European Development Centre for Inland and Coastal Navigation (VBD, 2002). Data sets for a total of 36 different units were presented. Furthermore, most of the units were presented with two or three different water depth-to-draught ratios, so that the total number of selected and processed test cases was 112. Of these, 58 were full-scale and the remaining 54 were model-scale test data sets. One case, or one data set, included at least three (but usually five or six) measured points of delivered power versus speed for a given service condition.

D5.2 Classes I to V: self-propelled vessels

Table D-3 gives the statistical analysis of the evaluation for a number of different subsets of data. The validation was conducted on the basis of power requirement calculated by the model, against the power delivered as measured for the corresponding condition during full-scale or model-scale tests. The model calculations were performed using a fixed overall propulsive efficiency of 0.5. This already introduces a ±10% error margin, assuming a propeller efficiency within the usual range of 0.45-0.55 as reported by VBD. The change of the overall propulsive efficiency over the speed range provides an obvious explanation for the deviation in model accuracy, since any error in the overall propulsive efficiency is directly transferred to the predicted power. On average, the results of the model appear close to the experimental data for all subsets, with the tendency to underestimate in the case of full-scale models (subsets D, E and G of **Table D-3**). This tendency is reduced with the assumption of lower propeller efficiency for these cases. This assumption is fully justified, as real conditions in restricted water are not ideal, resulting in a propeller operation which is far from the optimum. Similarly, higher propeller efficiency for the model tests where conditions are fully controlled would reduce, or even eliminate, the small overestimation observed on average (subsets C and F of **Table D-3**).

Table D-3: Statistical analysis of the model accuracy based on the estimated versus recorded delivered power (P_{est}/P_{rec}). Different subsets of the validation data are examined.

	A	B	C	D	E	F	G	H
Average	0.90	0.94	1.07	0.80	0.83	1.04	0.80	0.99
Average deviation	0.32	0.24	0.22	0.20	0.19	0.23	0.20	0.23
Standard deviation	0.42	0.30	0.29	0.25	0.24	0.30	0.25	0.29
Minimum value	0.18	0.23	0.23	0.31	0.41	0.20	0.28	0.43
Maximum value	2.40	1.95	1.95	1.55	1.55	1.95	1.55	1.95

A = All data sets included.
B = Data excluding extremely-shallow-water tests and questionable data sets.
C = Model test data excluding extremely-shallow-water tests.
D = Full-scale test data excluding extremely-shallow-water tests and questionable data sets.
E = Full-scale test data excluding extremely-shallow-water tests, questionable data sets, and the data sets showing considerable differences with corresponding model tests.
F = Model test data.
G = Full-scale test data excluding questionable data sets, and the data sets presenting considerable difference with corresponding model tests.
H = Data excluding shallow-water tests (h/T<2)[43] and questionable data sets.

Table D-4 shows the statistical analysis of the model performance per vessel class. It also shows the total number of validation points available per class, and how many of these points are from full-scale tests. The numbers in parentheses give the results for class IV after the removal of the two questionable data sets.

The results for the individual classes followed, for the most part, the trends observed in the subsets of **Table D-3**. Classes II and III, which were evaluated largely on the basis of model tests, showed an overestimation in the model calculations. Classes IV and V were evaluated based on full-scale tests, and thus showed an underestimation on average, especially when the questionable data sets, which skewed the distribution, were removed. However, class I also showed an underestimation, even though model-scale data were predominant in the validation. **Figure D-5** shows the trends in model agreement with respect to several of the fundamental parameters involved in the model. That the results are not dependent on these parameters indicates that the correction functional dependency is in the model. Removing the extremely-shallow-water tests and the questionable data sets improves the overall picture of the results in subset B as shown in **Figure D-6**.

[43] h/T = depth:draught ratio.

Table D-4: Statistical analysis of the model accuracy for the different vessel classes based on the estimated, against recorded, delivered power (P_{est}/P_{rec}). Overall propulsive efficiency = 0.5, all data sets included.

	Class I	Class II	Class III	Class IV	Class V
Average	0.78	1.16	1.06	0.99 (0.74)	0.79
Average deviation	0.20	0.20	0.23	0.42 (0.17)	0.19
Standard deviation	0.25	0.28	0.30	0.58 (0.21)	0.25
Minimum value	0.20	0.45	0.31	0.28	0.46
Maximum value	1.57	1.95	1.54	2.4 (1.42)	1.55
Total of data points	78	69	68	78	49
Full-scale data points	19	21	7	78	44

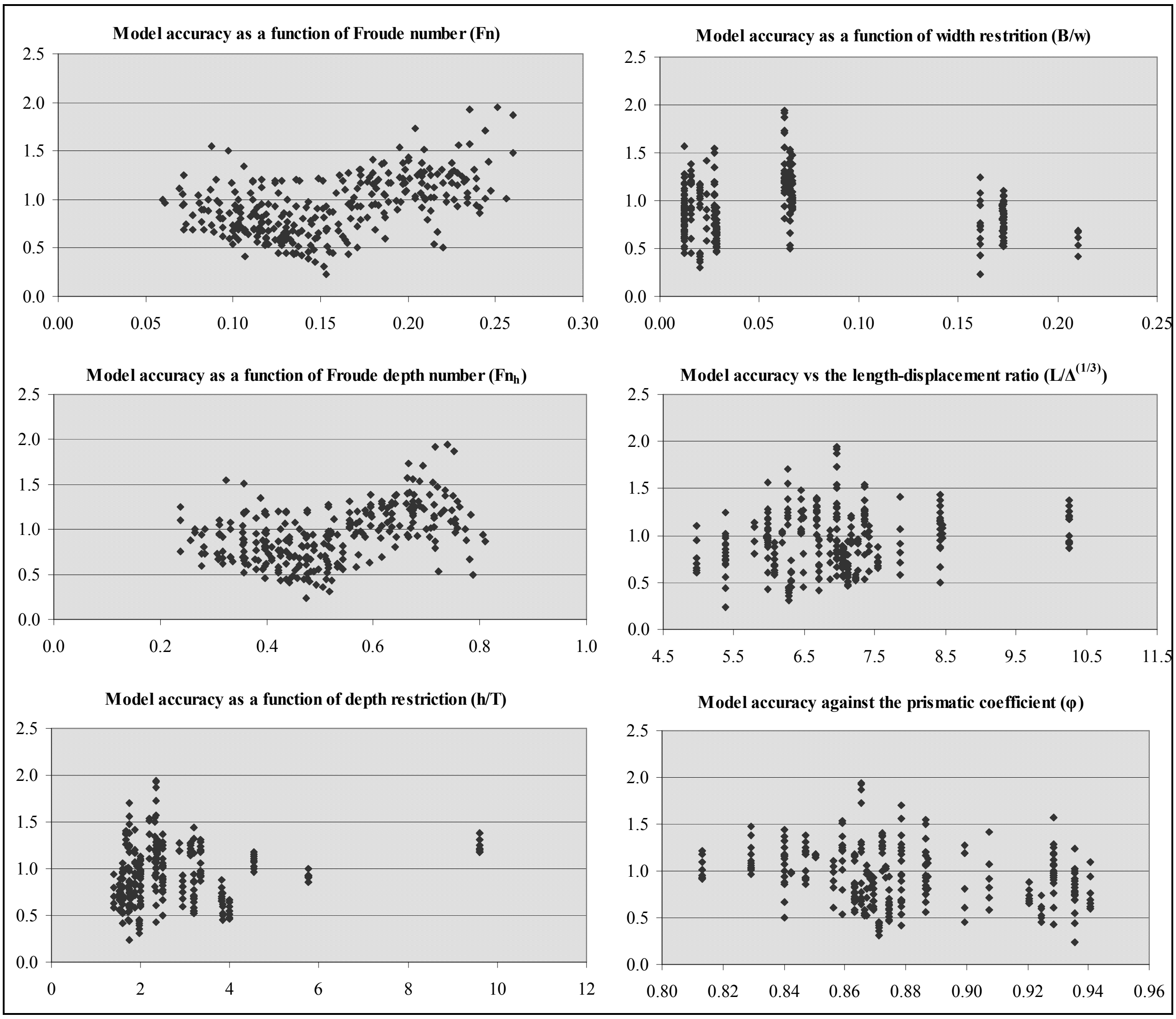

Figure D-5: Model accuracy as a function of different parameters. Questionable data sets and Extremely-shallow-water data excluded (subset B in **Table D-3**).

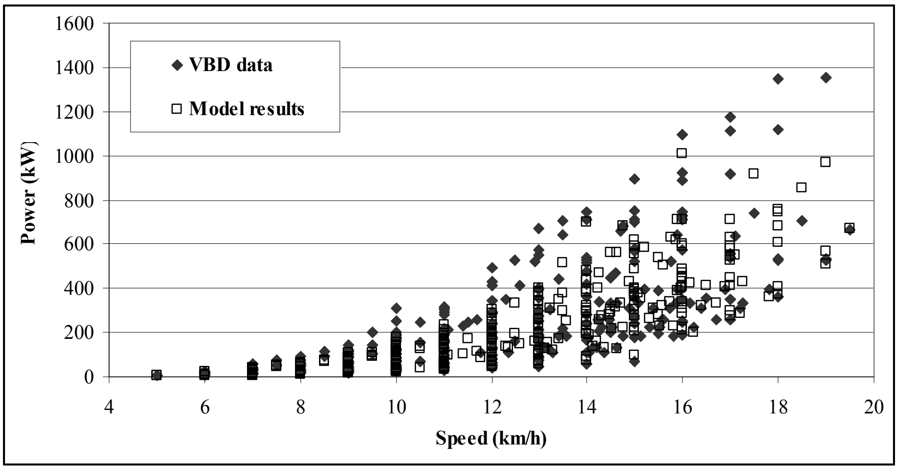

Figure D-6: Estimated versus recorded delivered power as a function of speed. Questionable data sets and extremely shallow water data excluded (subset B in **Table D-3**).

D5.3 Classes VI to IX: pushed convoys

Even though the model was built on methods for self-propelled vessels, it was also tested against results for pushed convoys. The calculation was performed assuming the convoy configuration to be a compact vessel of the same dimensions as the convoy. A fixed overall propulsive efficiency was also used in this case, with the lower value of 0.45 being selected. The results of this evaluation showed that the accuracy of the model was strongly dependent on the form of the convoy. The results for each class are shown in **Table D-5**.

Table D-5: Statistical analysis of the model accuracy for the different convoy classes based on the estimated versus recorded delivered power (P_{est}/P_{rec}). Propulsive efficiency = 0.45, all data included.

Class	VI	VII	VIII	IX	All
Average	0.92	0.54	0.80	0.72	0.76
Average deviation	0.38	0.21	0.07	0.26	0.26
Standard deviation	0.53	0.25	0.09	0.38	0.38
Minimum value	0.27	0.25	0.60	0.25	0.25
Maximum value	3.15	1.04	0.93	3.14	3.15
Data type	Full-scale	Model test	Full-scale	Mixed	Mixed

Class VI

This class refers to convoys of either a push-boat and two barges, or a motorship and a barge in-line. All the data were obtained from full-scale tests. One data set was overestimated by the model, with model values predicted to be almost double the recorded ones for most of the data points. The test was run at high speeds (over the economic speed limit for almost half of the points) and the recorded power requirement seemed to be low. The power demand of a motorship under the same conditions was more than twice the power recorded in this case. The Froude number was not greater than one, so this could not have been the result of a favourable reduction in the resistance in the supercritical area. It is more likely that there is an error in the recorded data set.

Class VII

This class includes configurations of a push-boat and two barges abreast or a motorship with a barge abreast. However, test data were only available for the case of the push-boat and barges convoy. All the data came from model-scale tests. The results in this case were not satisfactory, except in the case of large water depths. There was a clear trend of increasing accuracy with an increase in the depth-to-draught ratio, as shown in **Figure D-7**.

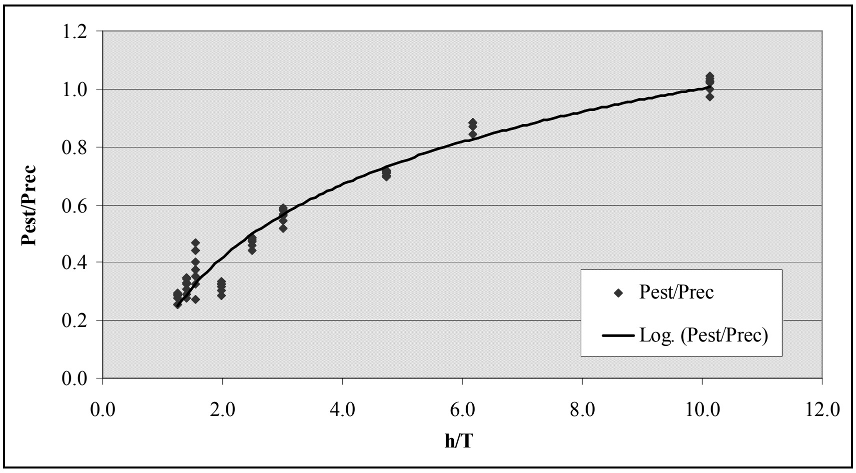

Figure D-7: Dependence of the model accuracy on the depth-to-draught ratio for class VII convoys.

An explanation for this is the increased breadth of the formation. Inland vessels have an advantage when moving through shallow water compared with their sea-going counterparts, due to their higher length-to-breadth ratio. By assuming a vessel with the characteristics of the abreast convoy formation, this advantage is lost and the 'vessel' moves in an unfavourable area of operation. The model does not account for this, as it is designed for inland vessels. Neither does it account for the complex hydrodynamics affecting convoys due to the flow between and around the barges. The effects of this interaction will be greater in shallow water.

Class VIII

This class refers to a convoy pushing four barges, in a two in-line by two abreast formation. All the available data were from full-scale tests. The results for this class were quite good, and consistent, with the model accuracy having an average of 0.8, an average deviation of 0.07, and a standard deviation of 0.09.

Class IX

This class refers to convoys of a push-boat and six barges, either in two barges abreast by three in-line, or three barges abreast by two in-line formations. Whilst the results were not good for either formation, there was again a small difference, with the model behaving better in the case of the two barges abreast by three in-line convoy, which represents the more streamlined configuration of the two.

D5.4 Classes VI to IX: pushed convoys, alternative method

A preliminary analysis of the basic model showed a dependency in the depth-to-draught ratio. An improvement was made by calculating the resistance using the polynomials from Marchal *et al.* (1996). The assumption of an overall propulsive efficiency of 0.45 was maintained, so that the results obtained using all methods would be comparable. The results for this version of the model were good, but had quite a large deviation, as shown in the first two columns of **Table D-6**.

Table D-6: Statistical analysis of the model using accuracy for the different convoy classes based on the estimated, against recorded, delivered power (P_{est}/P_{rec}). Resistance calculated according to the Marchal *et al.* (1996) polynomials. Overall propulsive efficiency = 0.45.

Data set	All*	All	A	B	VI*	VI	VII	VIII	IX
Average	1.02	1.06	0.99	1.08	1.12	0.98	1.04	0.94	1.02
Average deviation	0.25	0.29	0.20	0.16	0.31	0.20	0.15	0.24	0.20
Standard deviation	0.44	0.47	0.25	0.19	0.42	0.24	0.19	0.28	0.24
Minimum value	0.30	0.30	0.30	0.63	0.54	0.54	0.63	0.30	0.55
Maximum value	5.11	5.11	1.56	1.41	2.24	1.41	1.37	1.44	1.55

A. Points out of the model limits excluded except for those exceeding the *B*/*Bc*[44] lower limit only
B. All points out of the model limits excluded

[44] *B*/*Bc* is the width of the vessel divided by the width of the channel.

A comparison of the model accuracy with the important parameters of ship operation indicated no major trends. This is shown in **Figure D-8**. **Figure D-9** shows the predicted and measured engine power as a function of speed for all the convoy vessels in the VBD data set. It can be seen that with the Marchal *et al.* (1996) polynomials for resistance, good agreements was also obtained for convoy fleets.

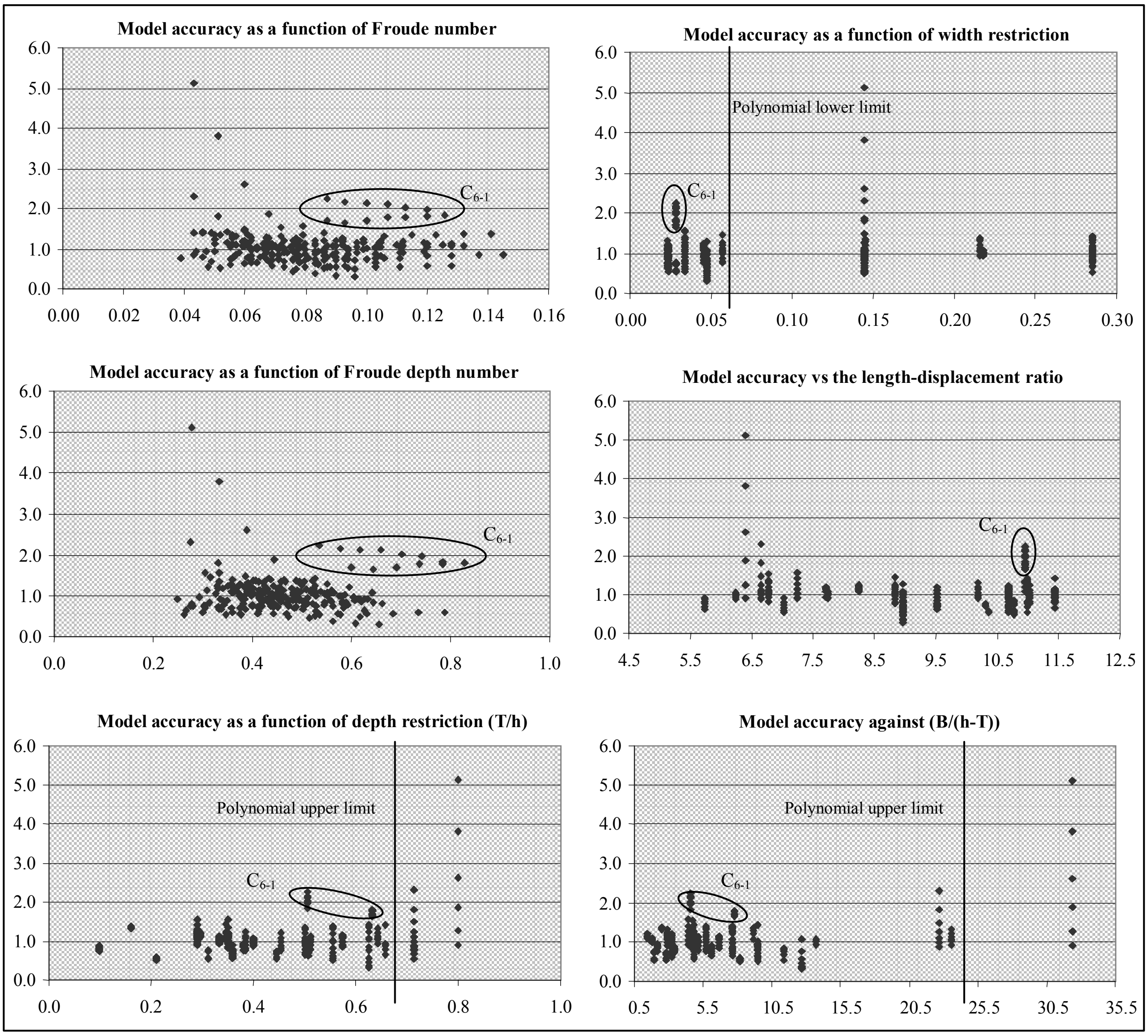

Figure D-8: Model accuracy for convoys as a function of different parameters. Resistance calculation according to the Marchal *et al.* (1996) polynomials (first column of **Table D-6**).

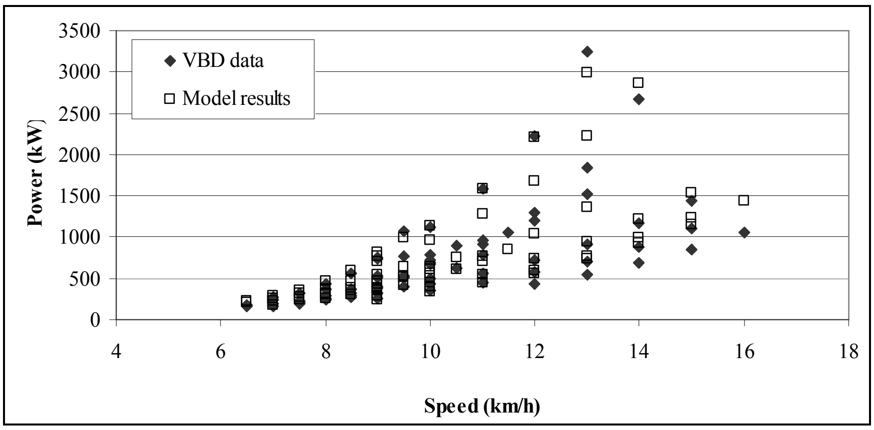

Figure D-9: Estimated vs. recorded delivered power as a function of speed. Resistance calculation according to the Marchal *et al.* (1996) polynomials. All data included (first column of **Table D-6**).

D6 Energy consumption of typical vessels

Some examples of the calculations performed using the inland shipping model developed in ARTEMIS are given in this Section of the Report for a number of typical ships under different service conditions. Since there is a single set of emission factors for all vessels involved, the focus is on the energy consumption of the vessels per transport unit (tonne-kilometre). The characteristics of the vessels used in the assessment are given in **Table D-7**. It was assumed that the freight carried accounted for 80% of the deadweight of a vessel, and this assumption was maintained for all load conditions. A propulsive efficiency of 0.5 was also assumed, and auxiliary engines were not taken into account.

Table D-7: Details of the vessels used in the assessment.[45]

Type	Class	Maximum length (m)	Maximum breadth (m)	Maximum draught (m)	Maximum tonnage (tonnes)
Spits / Peniche	I	38.7	5.05	2.2	364
O. Teubert	II	53	6.3	2.5	550
Kampenaar	II	50	6.6	2.5	638
New Kampenaar	II	55	7.2	2.5	638
Canal du Nord	III - V	60	5.75	3.2	800
DEK / G.Koenings (s)	III	67	8.2	2.5	968
RHK	IV	80	9.5	2.5	1,378
GMS / Large Rhine vessel	V	105	9.5	3.2	2,160
Tank ship	V	110	11.4	3.5	3,000
Container ship JOWI class	VIII	135	17	3	470 TEU
GMS + Europe II ‘in-line’	VI	185	11.4	2.5	4,000
GMS + Europe II ‘abreast’	VII	108.5	22.8	2.5	4,000
Pushed Convoy 2x2	VIII	190	22.8	2.5	7,700
Pushed Convoy 2x3	IX	265	22.8	2.5	11,500
Pushed Convoy 3x2	IX	190	34.2	2.5	11,500

Figure D-10 shows the calculated energy consumption per tonne-kilometre of goods carried for a typical class I vessel in a 40 m-wide canal. The ship is a so-called ‘Spits’-type self-propelled vessel. Similar graphs for typical vessels in all nine of the ARTEMIS classes are included below

Figure D-11 shows the energy consumption of a number of typical vessels operating in a shallow (2 m-deep) canal. The number in parentheses indicates the fraction of nominal draught that the vessel is able to maintain under such conditions. Service conditions like these are becoming more common due to climate change. **Figure D-11** clearly displays the economic speed limit, as there is a large increase in the energy requirement per tonne-kilometre between the speeds of 10 km/h and 11 km/h, whilst higher speeds are practically unattainable, especially for smaller vessels. It is likely that a speed limit lower that the previously mentioned values is in place to prevent damage to waterway banks.

A similar effect can be observed in **Figure D-12** for a slightly deeper and wider waterway. The rise in energy demand is now observed between the speed of 11 and 12 km/h. This is also visible in **Figure D-13**, where the curves referring to vessels with higher capacity utilisation cut across those of half-loaded larger vessels in the higher speed range. **Figure D-14** shows vessels operating in a deep, free-flowing river, where all vessels can achieve their design draught. Here, as expected, an economy of scale is evident, with large vessels demonstrating lower specific energy consumptions per tonne-kilometre of goods transported. The results are calculated for arbitrary conditions, and do not refer to specific waterways. However, they demonstrate that, with the relevant information available, a detailed profile of the energy economy of transport by inland waterways can be obtained, with reference to different routes or types of goods.

The model has been used to calculate the energy consumption for a series of vessels, including all the classes defined in the work, apart from class I ‘Spit’ vessels which were shown in **Figure D-10**. They are presented in the following Figures. Air pollutant emissions can be obtained from the energy consumption and the fuel specific emission factors in **Table D-2**, using a representative diesel heating value of 42 MJ/kg.

[45] Additional sources: Inland Navigation Europe (INE) and MAXX Logistics (MAXX Logistics: Library / Inland ship types : http://www.maxx.be/library/ships/index.html).

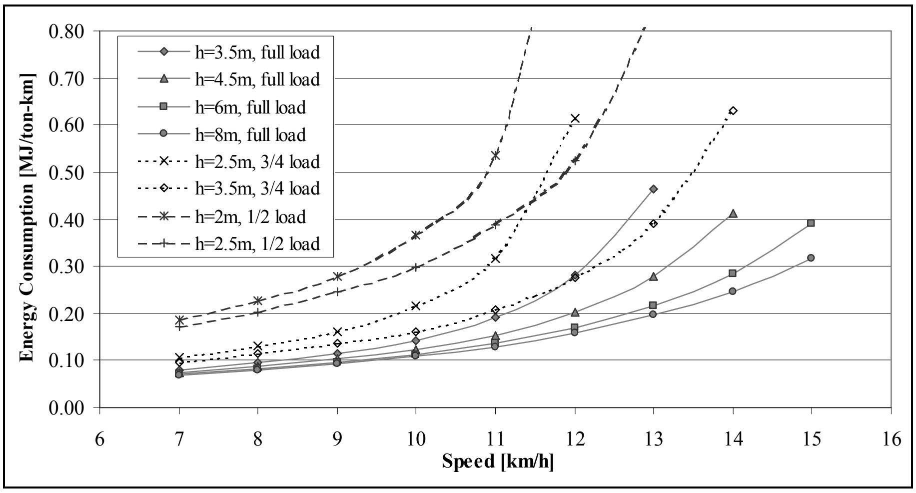

Figure D-10: Class I – 'Spits' vessel energy consumption results for a 40 m-wide canal.

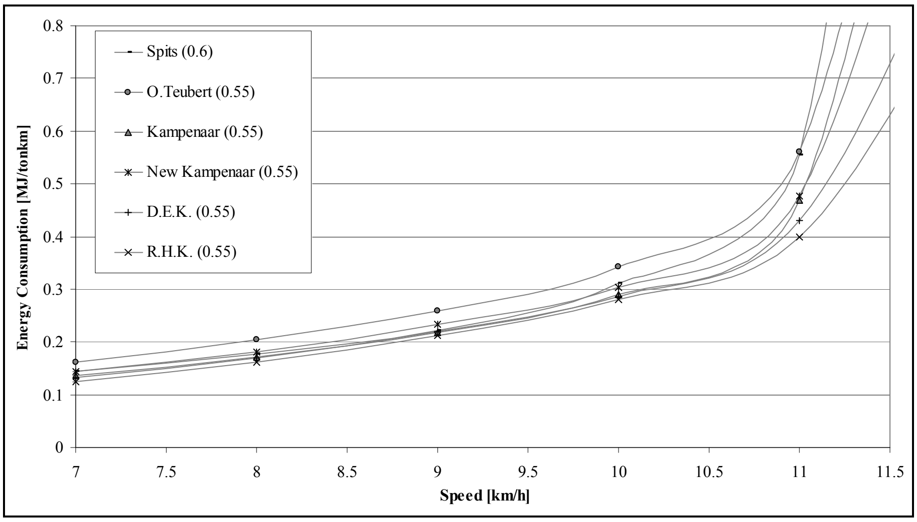

Figure D-11: Energy consumption of typical vessels for a 2 m-deep and 50 m-wide fairway.

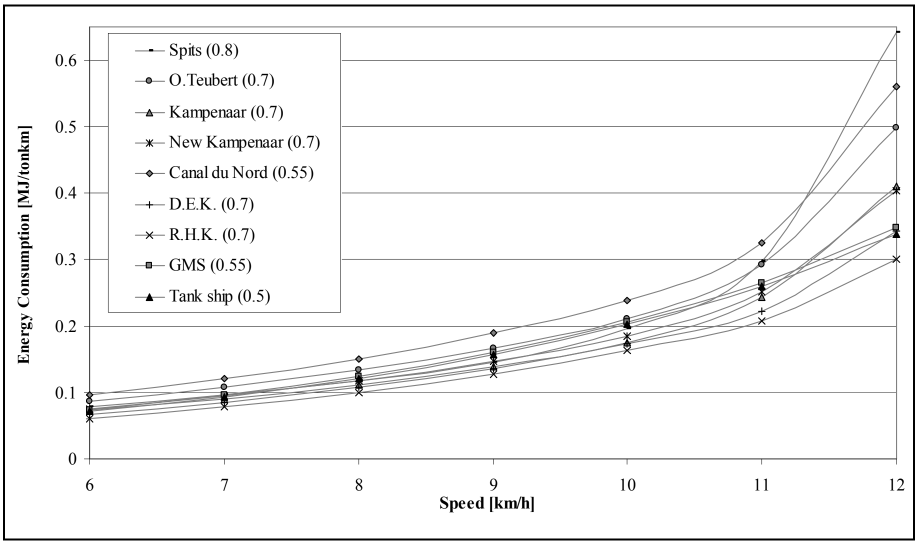

Figure D-12: Energy consumption of typical vessels for a 2.5 m-deep and 100 m-wide fairway.

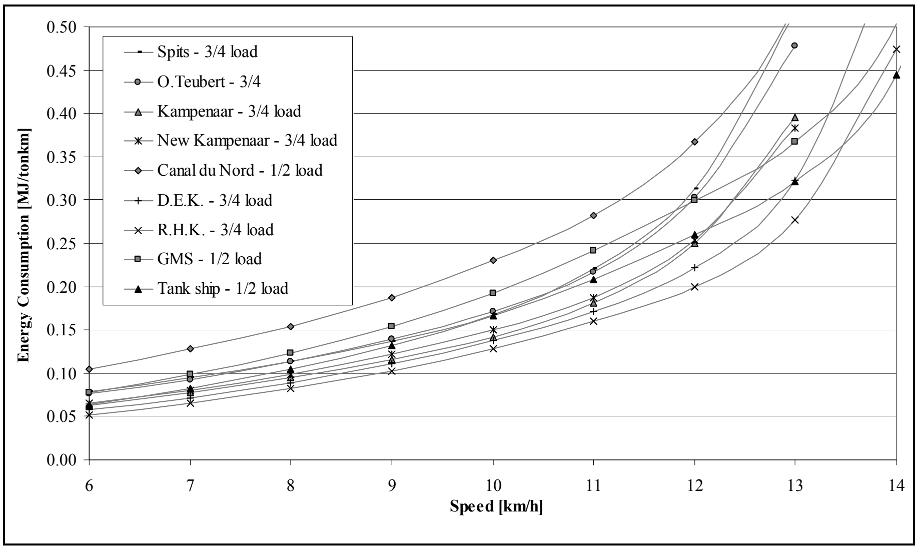

Figure D-13: Energy consumption of typical vessels for a 3 m-deep and 400m wide fairway.

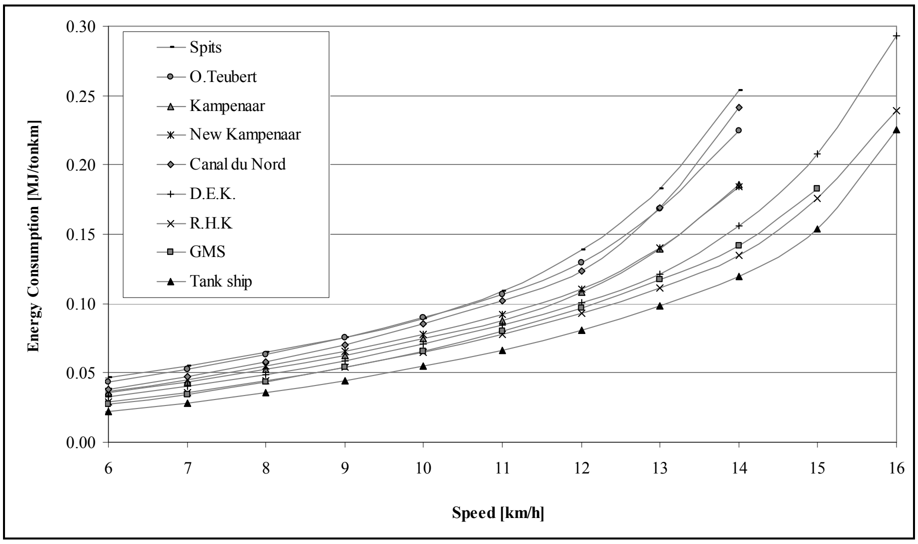

Figure D-14: Energy consumption of typical vessels for a 5 m-deep and 400 m-wide fairway (full load).

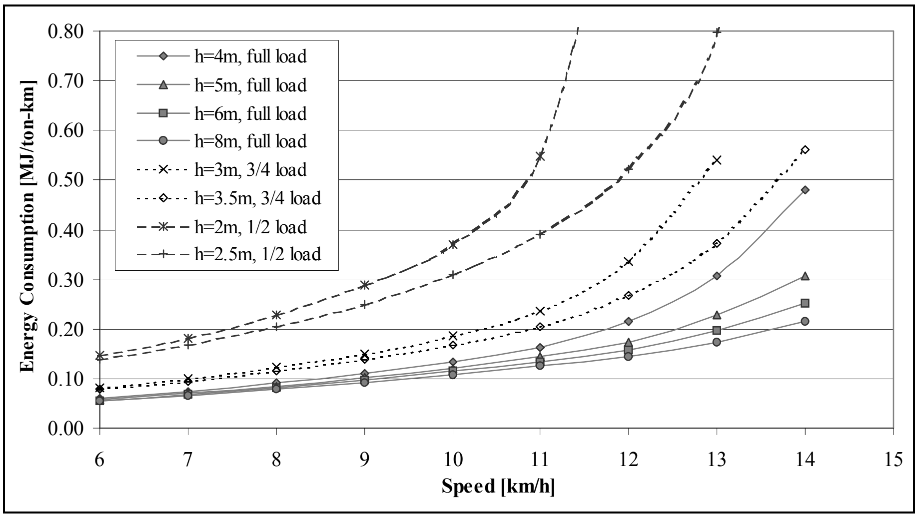

Figure D-15: Class II – 'O.Teubert' vessel energy consumption results for a 50 m-wide canal.

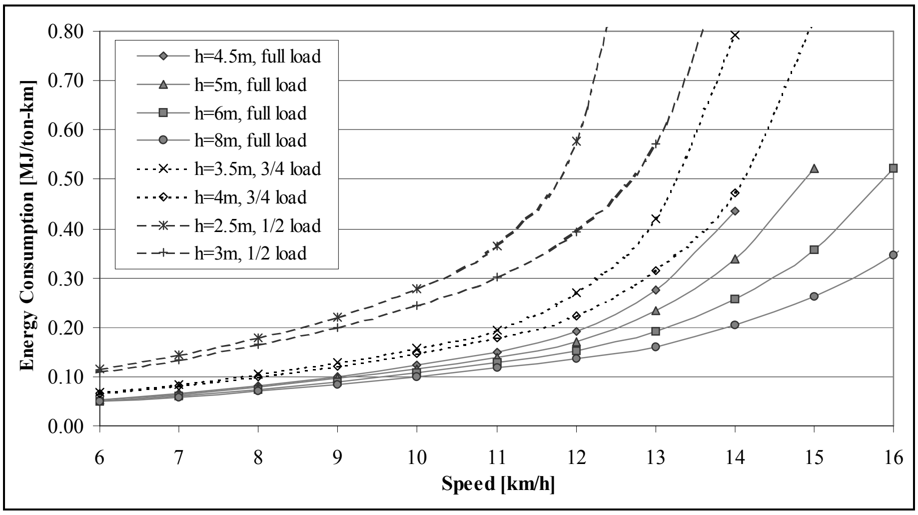

Figure D-16: Class III – 'Canal du Nord' vessel energy consumption results for a 50 m-wide canal.

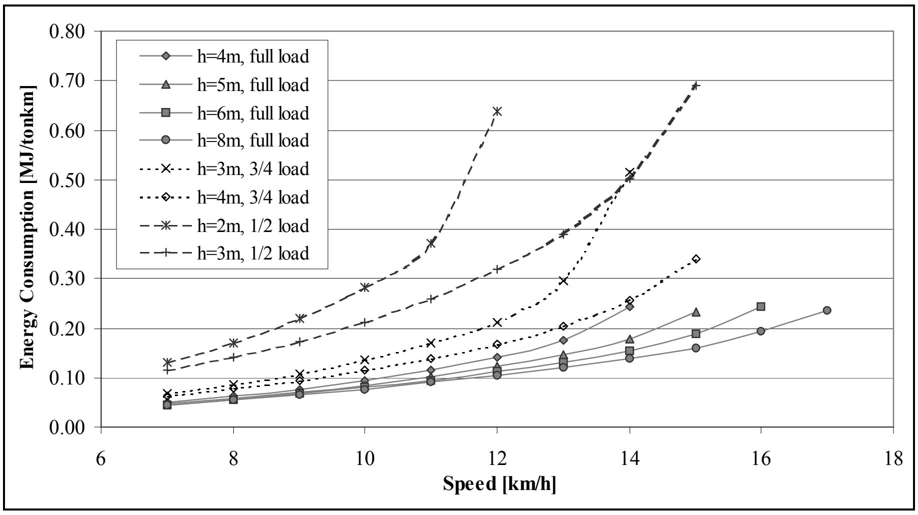

Figure D-17: Class IV – 'RHK vessel' energy consumption results for a 100 m-wide fairway.

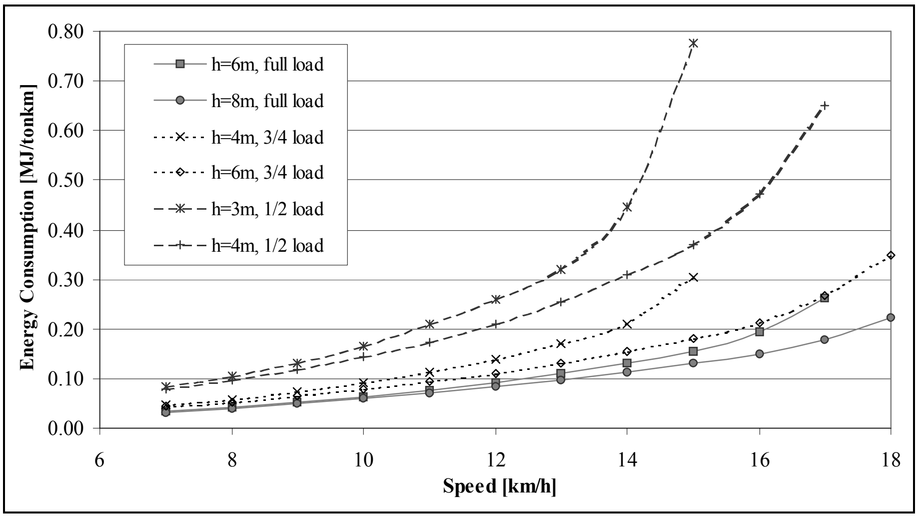

Figure D-18: Class V – 'Tank vessel' energy consumption results for a 400 m-wide fairway

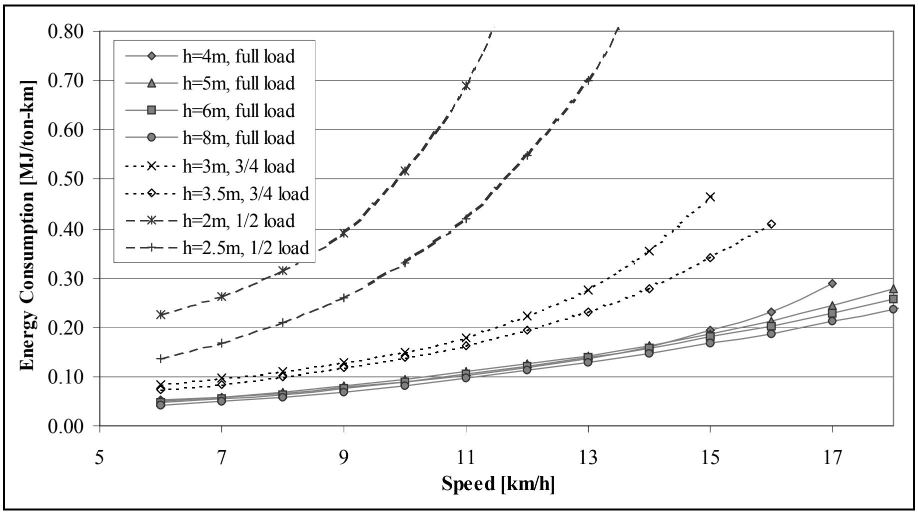

Figure D-19: Class VI – 'GMS + barge in line' energy consumption results for a 200 m-wide fairway.

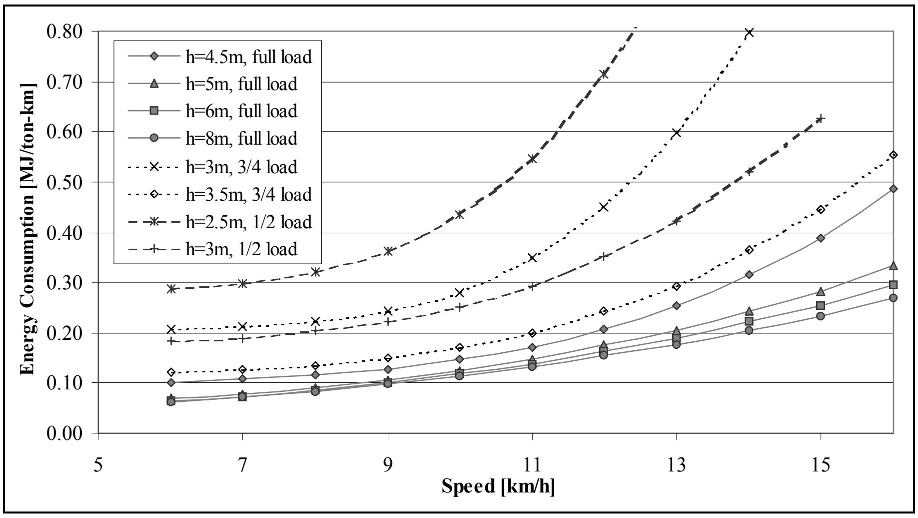

Figure D-20: Class VII – 'GMS + barge abreast' energy consumption results for a 200 m-wide fairway.

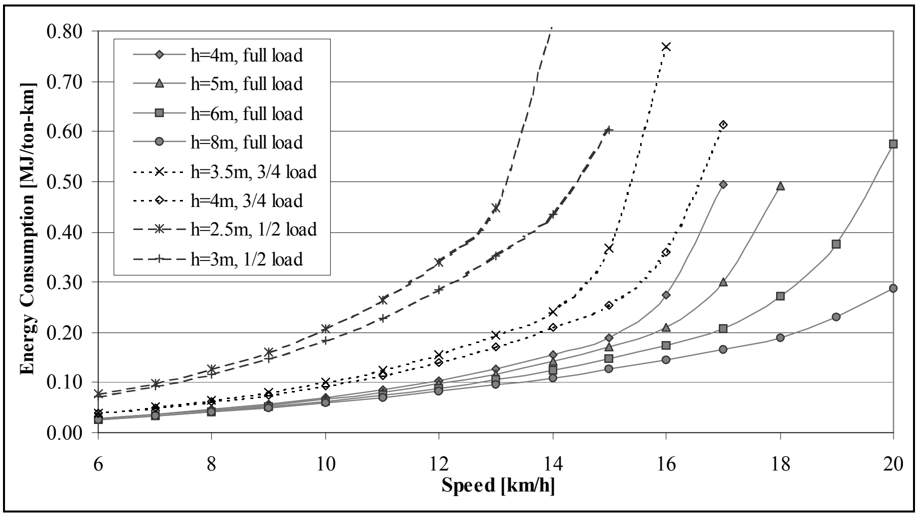

Figure D-21: Class VIII – 'JOWI-Container' energy consumption results for a 400 m-wide fairway.

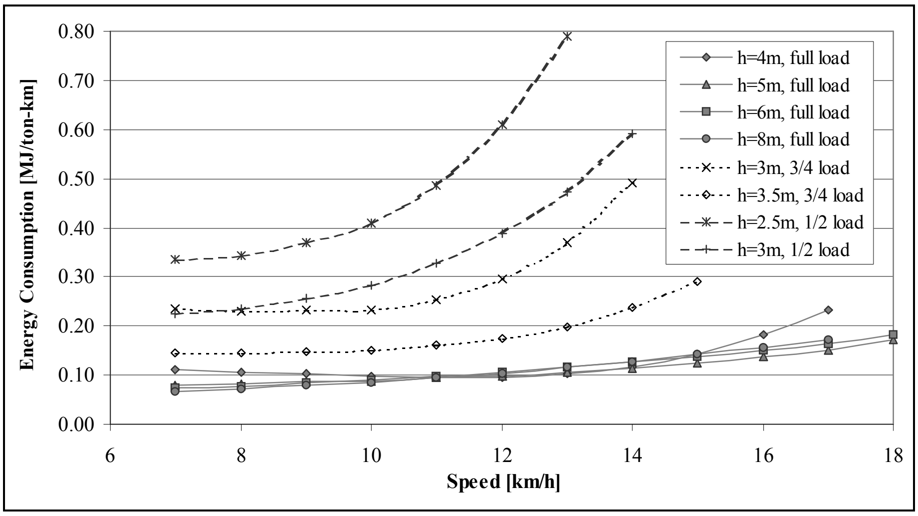

Figure D-22: Class VIII – 'Convoy 2x2' energy consumption results for a 350 m-wide fairway.

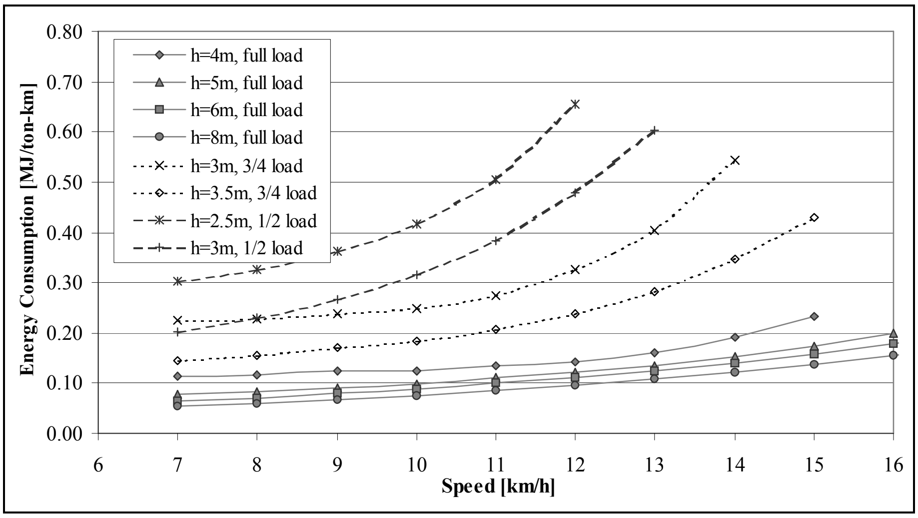

Figure D-23: Class IX – 'Convoy 2x3' energy consumption results for a 350 m-wide fairway.

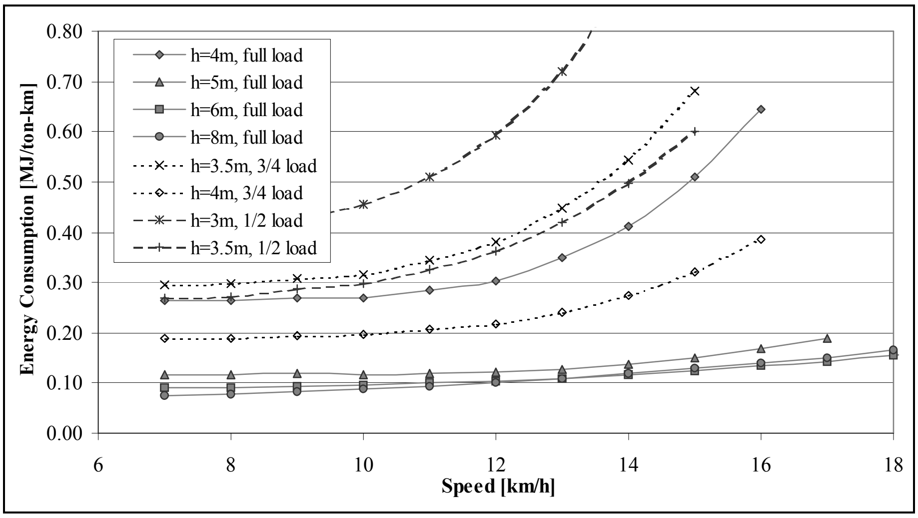

Figure D-24: Class IX – 'Convoy 3x2' energy consumption results for a 400 m-wide fairway.

D7 Future trends

D7.1 Fuel sulphur content

The sulphur content of marine gas oil used on the inland waterways must not exceed sulphur content of 0.2% by mass. This is to be further reduced to 0.1% by mass from 1 January 2008. The emission factors given so far correspond to sulphur contents of 0.15% to 0.17% in the fuel. It is obvious that the new measure will reduce these factors further by approximately 40% or more, depending on the actual sulphur content achieved. Furthermore, the reduction of sulphur contained in the fuel is also likely to influence PM emission favourably. The PM-sulphur content relationship used in the TRENDS project, which were based on correlations presented by Wall and Hoekman (1984) applied to marine fuel specifics, predicts a reduction of around 23% on values observed. This estimate was based on Lloyds reference emission factors and on assuming a new sulphur content of 0.1%. For PM the effect of other standards that may be introduced in the meantime are not taken into account. The effects of this measure can be incorporated in the present model by means of changing the emission factors used.

D7.2 Emission legislation

The first European legislation to regulate emissions from non-road (off-road) mobile equipment was formed in 1998 (Directive 97/68/EC). Regulations for non-road diesels were introduced in two stages, depending on the engine power output: Stage I (1999) and Stage II (2001-2004). However, engines used in ships, railway locomotives, aircraft, and generating sets were not covered by the Stage I/II standards.

The Central Commission for Navigation on the Rhine (CCNR, 1999) has proposed the values displayed in **Table D-8** as acceptable emission rates from diesel engines used in inland navigation. These values are equivalent to the Stage I standards.

Table D-8: Proposed acceptable emission rates by CCNR (1999).

Output (kW)	CO (g/kWh)	HC (g/kWh)	NO_x (g/kWh)	PM (g/kWh)
$37 \le P_N < 75$	6.5	1.3	9.2	0.85
$75 \le P_N < 130$	5.0	1.3	9.2	0.7
$P_N \ge 130$	5.0	1.3	$N \ge 2800$ rev/min = 9.2 $500 \le N < 2800$ rev/min = $45.N^{(-0.2)}$	0.54

The regulation applies to all engines of rated power (P_N) equal or grater than 37 kW installed on board vessels, or machines on board vessels which are not already covered by the EU Directives concerning exhaust emissions. The resolution would be in force from January 1st 2002 and would not apply to engines installed prior to this date or replacement engines installed prior to 31 December 2011, including engines installed on board vessels in service at 1st January 2002.

A proposal for Stage III/IV emission standards for non-road engines [COM(2002)765] was published by the European Commission in December 2002, and amended by the Parliament in October 2003. Marine engines used for inland waterway vessels are included in the Stage III/IV standards, but have somewhat different emission limits, as shown in **Tables D-9** and **D-10**. The Stage III standards entered into force from 2006, whilst the Stage IV standards will be phased-in between 2010 and 2014. The Stage III/IV legislation applies only to new vehicles and equipment; machinery already in use can continue using Stage I/II engines, even when engines are replaced.

Table D-9: Proposed Stage III limits for inland waterway vessels.

Category	Displacement (D) (dm^3 per cylinder)	CO (g/kWh)	NO_x + HC (g/kWh)	PM (g/kWh)	Date
V1:1	$D \le 0.9$ and $P > 37$ kW	5.0	7.5	0.40	31.12.2006
V1:2	$0.9 < D \le 1.2$	5.0	7.2	0.30	
V1:3	$1.2 < D \le 2.5$	5.0	7.2	0.20	
V1:4	$2.5 < D \le 5$	5.0	7.2	0.20	31.12.2008
V2:1	$5 < D \le 15$	5.0	7.8	0.27	
V2:2	$15 < D \le 20$ and $P \le 3300$ kW	5.0	8.7	0.50	
V2:3	$15 < D \le 20$ and $P > 3300$ kW	5.0	9.8	0.50	
V2:4	$20 < D \le 25$	5.0	9.8	0.50	
V2:5	$25 < D \le 30$	5.0	11.0	0.50	

Table D-10: Proposed Stage IV limits for inland waterway vessels.

Category	Displacement (D) (dm^3 per cylinder)	CO (g/kWh)	NO_x + HC (g/kWh)	PM (g/kWh)	Date
V1:1	D ≤ 0.9 and P > 37 kW	5.0	1.5	0.02	31.12.2010
V1:2	0.9 < D ≤ 1.2	5.0	1.5	0.02	
V1:3	1.2 < D ≤ 2.5	5.0	1.5	0.02	
V1:4	2.5 < D ≤ 5	5.0	1.5	0.02	31.12.2011
V2:1	5 < D ≤ 15	5.0	1.5	0.02	
V2:2	15 < D ≤ 20 and P ≤ 3300 kW	5.0	1.7	0.02	
V2:3	15 < D ≤ 20 and P > 3300 kW	5.0	2.0	0.02	
V2:4	20 < D ≤ 25	5.0	2.0	0.02	
V2:5	25 < D ≤ 30	5.0	2.2	0.02	

It is not possible to predict the effect of these measures without more information on their implementation and on the replacement rates for engines in the fleet. However, it is fair to say that by observing the dates after which the standards will enter into force, and recognising the long working lives of the engines in question, these regulations will not have any considerable effect on the emission levels for another couple of decades. Consequently, the TRENDS predictions for NO_x should remain more or less valid until 2020. Incentives provided or supplementary policies may speed up the process, but the fact remains that inland shipping is following other modes rather slowly in the subject of emission regulation. Still, the scale effect ensures that it is still a rather energy-efficient transport mode.

D7.2 Emission modelling and GIS

The GISCO[46] Water Pattern layer of the Hydrography Theme includes a subset showing the navigable waterways of Western Europe. Other attributes of the data set are the identification of the type of waterway and its navigability as well as the existence of bottlenecks. In view of the European Commission's interest in GIS applications, the connection of the ARTEMIS inland model to GISCO was examined. This could provide an indicator of energy consumption per ton-kilometre travelled for different types of vessel on a specific river segment or, taking into account the traffic split, an average efficiency over the segment could be provided, along with overall emission estimates. However, due to the lack of detailed representation of the inland waterway network and traffic in the GISCO database this has not been possible. No average dimensions of the rivers or canals are given, and the indication of the segments navigability is not in agreement with the European Conference of Ministers of Transport Resolution. However, the design and operation of the model is clearly geared to this direction and may be used in this way in the future. A correlation can be devised between the classes, but more information on the waterways, such as traffic patterns and average depths and the time they are maintained for, is needed before a connection with GISCO has any meaning.

Applications are still possible on a local scale, by retrieving waterway information from regional monitoring organisations which record the water level on different waterways over the year. This would require dividing the year in periods with similar average water depths and calculating the energy consumption of typical vessels on the waterway for that period. As this information is not processed and organised in a database that can be connected to ARTEMIS, this requires considerable time and effort.

The development of River Information Services (RIS) is likely to provide a good source of information on the waterway characteristics. RIS is a concept of harmonised information services to support traffic and transport management in inland navigation. One of the main functions defined is the Fairway Information System (FIS) that is to supply actual and predicted water levels and currents. The Inland Navigation Demonstration for River Information Services (INDRIS) led to the Consortium for the Operational Management Platform for River Information Services (COMPRIS), which aims to establish a pan-European RIS by 2005 (Pfliegl, 2002). Since this activity involves making preliminary assessments of waterway conditions and traffic as well as developing an electronic nautical chart for all navigable waterways, it is hoped that the data necessary to also connect emission calculations to GIS will be easier to obtain in the future.

D8 Summary and conclusions

This Part of the Report has described the ARTEMIS work on inland shipping. Nine ship classes were established, based on a vessel's size and the waterways it is able to navigate. A technical model, which had previously been partially developed by DTU, was improved and validated using experimental data provided by the European Development Centre for Inland and Coastal Navigation. Special focus was put on the specific fuel consumption of engines used on inland shipping vessels, as

[46] http://www.aris.sai.jrc.it/data-dist/search-tools/metadata/index.html?plain

this was an area of considerable uncertainty, and a correlation was developed to provide specific fuel consumption values according to the engine output. The uncertainty is thus greatly reduced as the values provided by the correlation are within the error margins given by the manufacturers. The model developed for inland shipping in ARTEMIS is already in use for the TREMOVE project.

Some guidelines for the input parameters required by the user were presented by Georgakaki and Sorensen (2004). These include average waterway width, depth and speed limits, the share of different vessels on the waterway, and their average load. As the model is intended for non-expert users there is a provision for most of the parameters to be set to default values.

The model was validated for a wide variety of service conditions, giving priority to data arising from full-scale measurements. The conditions that could not be covered by full-scale tests were covered by model towing-tank tests. The validation showed that the model results correlated well, on average, with experimental data, but the deviation could be considerable. After careful examination of both the methods used and the results produced, this was attributed to the number and complexity of the parameters involved, as well as to the large range of vessel types and operational conditions. The fact that no systematic inaccuracies were observed with regards to any of the major factors involved in the calculation supports this view. The accuracy of the predicted engine output against measured values was between 80% and 107%, with the deviation ranging from 19% to 30%. The model performance was therefore deemed acceptable for the purpose of ARTEMIS, which is to provide average indicators for the entire fleet and not precise values for single vessels. Thus, it operates on very little input data, with a trade-off in accuracy being inevitable. The model was also found to work well for operation in less restricted waterways. Individual cases, for which the deviation of the prediction from the measurement was large, could usually be attributed to vessels sailing under extreme conditions or problems with either the vessel or the measurement procedure. As long as the limits and guidelines for the input parameters are observed, the model presented should provide a reasonable estimate of the operation of an average vessel of the type and size in question under the given service conditions.

The model was subsequently been put to use to provide examples of indicators that may be produced for typical vessels in service under different conditions. These calculations gave an idea of how the different parameters (speed, draught, waterway depth, *etc*.) influence the energy consumption of inland vessels. The results were calculated for arbitrary conditions, and did not refer to specific waterways. However, they demonstrated that, with the relevant information available, a detailed profile of the energy economy of transport by inland waterways could be obtained, with reference to different routes or types of goods. This would require better knowledge of both waterway characteristics and traffic statistics. The following are aspects need be investigated further:

- Average waterway, width, depth and speed regulations.
- Number of days per year a certain average depth is maintained per waterway.
- Share of each vessel type that operates on a given waterway.
- Average speeds for upstream and downstream navigation for a given vessel type.
- Average load factors for upstream and downstream navigation for a given vessel type.
- Number of locks and average time for lock passage per route

Information on some of the above points exists in the form of studies performed by local authorities, but statistics reported to EUROSTAT are not of such detail. Still if there is specific interest for a route or type of cargo the model results should provide an easy way to evaluate transport choices involving inland shipping.

Some future trends relating to emissions from inland shipping were also discussed, including fuel sulphur content, emission legislation, and the use of GIS.

The sulphur content of marine gas oil used on the inland waterways is to be further reduced to 0.1% by mass from 1 January 2008. The effects of this measure can be incorporated in the ARTEMIS model by means of changing the emission factors used. The reduction of fuel sulphur is also likely to influence PM emission favourably, and the TRENDS model can be used to predict these reductions. For PM, the effect of other standards that may be introduced in the meantime are not taken into account.

Proposed Stage III/IV emission standards for non-road engines have been published by the European Commission. It is not possible to predict the effect of these measures without more information on their implementation and on the replacement rates for engines in the fleet. However, the long working lives of ship engines means that the regulations will not have any considerable effect on emission levels for another couple of decades.

Connections between the ARTEMIS inland model and the GISCO information on navigable waterways of Western Europe was examined. However, due to the lack of detailed representation of the inland waterway network and traffic in the GISCO database no linkage was possible. Applications are still possible on a local scale, by retrieving waterway information from regional monitoring organisations which record the water level on different waterways over the year. As this information is not processed and organised in a database that can be connected to ARTEMIS, this requires considerable time and effort. The development of River Information Services (RIS) is likely to provide a good source of information on waterway characteristics, and it is hoped that the data necessary to also connect emission calculations to GIS will be easier to obtain in the future.

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PART E: MARITIME SHIPPING

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E1 Background

Maritime shipping describes transport activity which takes place upon the sea or in sea ports. Some of the first attempts at estimating emissions from maritime shipping were undertaken in the early 1990s, when the sector was identified as a likely area of future concern. One reason for this was the high level of sulphur in shipping fuel, given the problems of acidification in Scandinavia. In addition, few technical measures had been introduced to reduce emissions from the sector. The focus of attention has gradually turned towards maritime shipping, and more recent work undertaken in the CAFE programme has shown that, in the context of further action to reduce environmental and health risks, additional measures to reduce pollutant emissions from ships are likely to be cost-effective. For example, the CAFE baseline projections indicate that in 2020 maritime activity will be one of the major contributors to NO_x and SO_2 emissions (Amann *et al.*, 2005). Furthermore, greater consideration is now being given to the role of maritime shipping in emission trading schemes.

The user of an emissions model for maritime shipping would typically wish to quantify total pollutant emissions on a range of different scales, from individual ports to large sea areas. The most important pollutants are CO, NO_x, HC, SO_2 and PM. Fuel/energy consumption and CO_2 emission estimates are also often required, and there is often a need for emissions to be presented both in terms of line sources along routes and as point sources within ports.

This Part of the Report summarises the results of the maritime shipping work in ARTEMIS, and is largely taken from the work by Sjöbris *et al.* (2005). Subsequent Sections of Part E describe some previous studies and models relating to maritime shipping, some of the limitations of models, the development of the ARTEMIS model, and the final emission estimation approach. Some conclusions and recommendations for future work are also presented. Sjöbris *et al.* (2005) also discuss at length emission legislation and emission-reduction schemes and incentives in the sector. For reasons of brevity, this discussion has not been included here.

E2 Previous studies and models

E2.1 MariTerm studies

Between 1990 and 1991 a study was performed by MariTerm AB on behalf of the Swedish Maritime Administration and the Swedish Ship Owners Association (Alexandersson *et al*., 1993). The study covered three main areas: (i) the state of the art regarding ship engines, fuels and emissions, (ii) an assessment of emissions in the Baltic Sea Area (BSA), based on a database containing port information, and (iii) the technical measures available to reduce emissions, with estimates of cost.

Models were created to determine fuel consumption in relation to the types and sizes of vessel and engine in service. The distance travelled by a ship was defined as the distance from the port to open water plus the additional distance along the closest route to the North Sea or, if the port of destination was within the BSA, half the distance to the next port. The input to the model was port call information, which was obtained directly from the ports due to the absence of a central register. As most of the ports used GRT[47] for port dues, the size of the ships were assigned in groups in accordance to their GRT. Ferry services were modelled based on timetables. The following parameters were also determined: average engine power, the power of auxiliary engines, and the speed at 80% MCR[48]. Ferry operation during a passage was modelled in five stages: (i) start up and departure, (ii) departure from the port, (iii) cruising, (iv) approach and (v) berthing. Emission factors were determined as a function of tonnage.

The conclusions of this work, which to some extent are still relevant today, included the following:

(i) Shipping movements were poorly recorded, with there being no reliable centralised database.

(ii) Ferries and trading ships were well covered in the database.

(iii) There was no register of fuel use by type and quantity.

(iv) Emission factors for ship engines were not available, and manufacturers kept no records of emission factors for each engine.

(v) Most of the ships had engines which were optimised to minimise energy use, resulting in high NO_x emissions.

(vi) Measurements on engines showed a wide range of emission levels, not only between engines but also between cylinders within a single engine.

(vii) Ships were viewed as an outlet for oil residues from refineries.

(viii) There was little concern about the sulphur content of marine fuel. Indeed, sulphur was regarded as being necessary for engine operation.

Since 2000, the assessment methods used by MariTerm for the Swedish Maritime Administration have been based upon information on shipping movements recorded by Lloyd’s Maritime Information Services (LMIS), and relationships between

[47] GRT = gross tonnage according to the Oslo Convention, which was the relevant at the time.

[48] MCR = maximum continuous rating. The stated operating limits assigned to an engine by the manufacturer, which defines the power at which the engine may be operated for an unlimited period under specified conditions.

energy consumption, GT[49] and speed from the MEET project (see below). Ferry services are added from the Shippax traffic database. As there is some overlap of information between LMIS and Shippax, a special routine is used to identify the corresponding cases, and allows the operator to choose which source is to be used. A computer application runs through all shipping movements, and allocates the emissions to pre-defined areas using the Veson port distance database[50] for the North Sea, the BSA and shipping movements in Sweden.

E2.2 MEET model

In the maritime sector, one of the most commonly used models is the one produced in the Fourth Framework MEET[51] project (European Commission, 1999). The MEET model was a simple but reliable tool for calculating emissions and fuel consumption from ships of various types and sizes, as well as for different types of marine engine. The model was also based upon information from LMIS, and covered approximately 15,000 vessels, of which 11,000 had an assigned GT. Correlations between fuel consumption (in tonnes per day) at full power and GT were derived for a limited number of ship classes, and emissions were estimated from the fuel consumption values using fuel-specific emission factors. MEET also presented functions to enable the calculation of emissions and fuel consumption for different types of operation, such as cruising, manoeuvring and hotelling, and for auxiliary engines used to supply electricity. The emissions factors in MEET were obtained from a review of the literature.

E2.3 TRENDS model

The TRENDS[52] project produced a *Database System for the Calculation of Indicators of Environmental Pressure Caused by Maritime and Inland Shipping_Transport* (Georgakaki *et al.*, 2002). The types of ship included in the database were, to a large extent, based on the *Lloyd's Register of Shipping* (referred to hereafter as *Lloyd's Register*). The relationships between fuel consumption and ship size were based upon GT and DWT[53]. Activity data were taken from EUROSTAT 1970-2002, both for maritime freight transport and maritime passenger transport. Gaps in the statistics were filled using data from national sources. The distances between 'port pairs' were identified from distance tables. Cargo type was included as part of the method, with the demand for aggregated cargo and commodity flows being taken from similar assessments for road transport. In TRENDS, an attempt was also made to allocate ship characteristics to countries and ports, although as the use of ship types varies with the market this was somewhat uncertain. More information is required in the future to enable the allocation of emissions to commodities.

E2.4 SMED study

SMED (Swedish Methodology for Environmental Data) has derived emission factors for ships (>100 tonnes) to be applied in Swedish international reporting (Cooper, 2004). The study focussed on 28 air pollutants, where the emission factors have been proposed as a function of engine and fuel type. For the year 2002, the factors cover three operational modes (at sea, manoeuvring and in port), and thereby take into account main engine and auxiliary engine emissions. A set of 'at sea' emission factors have also been prepared covering the period 1990 to 2001 to allow an update of the marine emission time series.

In order to obtain representative and up-to-date emission factors for this application, Swedish data held by IVL and others, combined with published sources were assessed. Emission factors were thus derived from a database consisting of exhaust measurements from approximately 62 ships, involving approximately 180 marine engines. The emission factors were subsequently weighted to account for the proportion of the fleet using exhaust gas after-treatment systems, age deterioration effects related to fuel consumption and the increased use of lower sulphur fuels. Finally thus study also investigated emission factor uncertainty (Cooper, 2004).

E2.5 ENTEC study

This study, undertaken for the European Commission, examined the cost, emission reduction potential, and practicality of several different NO_x/SO_x abatement technologies for main and auxiliary engines on ships. The study also addressed the use of shore-side electricity, and included a market survey of the availability of low-sulphur fuels in Europe. (ENTEC, 2002). The ENTEC study was based entirely on information from Lloyds Maritime Intelligence Unit[54] relating to observed movements of freight ships of 500 GT and above. Data on four months in 2000 were analysed and extrapolated to estimate freight ship movements and port callings per vessel type in the year 2000. Ferry movements were estimated by identifying

[49] GT = gross tonnage according to the London IMO Convention of 1969. The GT is related to the enclosed volume of the ship, but is a constructed figure.
[50] http://www.veson.com/
[51] MEET = Methodology for calculating transport emissions and energy consumption.
[52] TRENDS = Transport and Environment Database System.
[53] DWT = Deadweight tonnes, a figure that includes the ships carrying capacity in metric tonnes including cargo, bunker and stores.
[54] LMIS became Lloyds Maritime Intelligence Unit in 2001.

the maximum number of crossings possible in one day, and applying seasonal ratios to derive the real number of crossings per day. The ratios were derived from published timetable information for selected ferries. ENTEC reported maritime movements by ship type, by engine type and by fuel used, and noted that the engine type and the fuel used largely dictate a ship's emissions, irrespective of ship category (container, passenger ferry, *etc.*). Emissions were plotted in a GIS grid. Based on a combination of manufacturer specification and measurements from different sources, the study produced three tables of emission factors (and total emissions for 2002) for different ship types, relating to operation at sea, in port, and during manoeuvring.

E3 Limitations of previous models

E3.1 Activity data and commodity flows

During the last decade, one of the most significant limitations of maritime shipping models has been the poor quality of the activity data, and an absence of year-on-year consistency in the statistics. Indeed, there is still no general system for describing sea transport statistics, probably because of the absence of adequate records. It has therefore been rather difficult to describe trends in emissions.

Freight and commodity statistics have never been harmonised for maritime shipping. This problem will probably increase in the future, as the refinement of sea transport systems allows a variety of products to be shipped in cargo units that are transported on different types of ship, and load carriers like containers may contain anything from bulk to computer software. This prevents databases being constructed in a way which would allow connections to be made between commodity flows and sea traffic. Given the variety of transport options, a huge database would be required in order to keep track of commodity flows by ship type. It is possible, however, that detailed movements of cargo could be handled statistically but also this demands information upon which to base statistics and to keep track of changes. The only straightforward means of understanding how commodities are moved by sea is to study vessel movements between ports, and to link these to commodities which are known to be shipped in particular types of ship.

Statistics relating to ferry operation are simpler and better recorded. The total activity is undertaken by a controllable number of ships, and the frequency of port calls is high. The vast majority of services are 'pendulum' services between two ports.

E3.2 Vessel speed

Neither MEET nor TRENDS used ship speed as a model input, although in practice it has a significant effect on fuel consumption and emissions.

E3.3 Harbour operations

The MEET procedure provided estimates of fuel consumption levels for different types of operation in harbours. The area of harbour emissions is not covered very thoroughly in the MEET and TRENDS work, yet it can be very important with regard to local emissions in shipping centres.

E4 ARTEMIS objectives

For maritime shipping, the overall objective of the ARTEMIS work was to produce a relevant, user-friendly tool for the assessment of in-service emissions and fuel consumption, building upon the work of the COST 319 Action[55] and the MEET project. Furthermore, the project was designed to assemble data and statistics relating to the market, port activity and national shipping.

The specific objectives of ARTEMIS, which were addressed, to a greater or lesser extent, can be summarised as follows:

(i) To re-evaluate shipping categories. At the start of ARTEMIS there was a need to re-evaluate existing data in order to determine whether the vessel classifications used in previous models were appropriate and optimal. The system of classification needed to distinguish between ship types on a technical basis, as well as realising the potential for the model user to obtain information in relation to these types and their associated activity data. There was also the possibility that geographical factors might need to be included in the classification.

(ii) To improve the knowledge of operational conditions and fuel consumption in harbours. Much more extensive and accurate data were needed to estimate emissions from ships in harbours. Technical factors such as fuel consumption during different types of harbour operation, auxiliary engine power levels, and additional emission factors for operation during these modes were necessary. Activity data, relating to the amounts of time spent in the various modes of harbour operation, were also required.

[55] COST 319 = Estimation of pollutant emissions from transport. http://www.cordis.lu/cost-transport/src/cost-319.htm

(iii) To provide a better description of ferry operation. Specific data were required on ship size, fuel consumption and loading for different types of ferry. Data were also required for different areas in Europe where ferry traffic is important, such as Greece, the BSA, the North Sea and the English Channel.

(iv) To compile the results and construct a model. The results from above tasks had to be compiled and evaluated in order to develop relationships between emissions and parameters which end users could be expected to have at their disposal. Results from other studies of emissions from maritime shipping were to be obtained, analysed and, where relevant, incorporated into the methodology. The aim was to develop models that were open and accessible for future modification, easy to upgrade for future developments in fuels and emission control technology, and suitable for use in a database format similar to that being developed in the TRENDS project.

(v) To provide a better verification of the model accuracy.

(vi) To estimate future trends. Since strategic comparisons between transport modes involve future systems, it was necessary to try to estimate future developments and trends in the important parameters for modelling, in particular vessel fuel consumption and emission factors.

E5 ARTEMIS model development

E5.1 Overview

During the development of the ARTEMIS maritime shipping model, the underlying philosophy was to develop an approach which could be recognised and accepted by the shipping industry, and would therefore be useful in a wide range of applications. It was therefore vital that the methodology was based on undisputed data, although some assumptions were required for the emissions of some pollutants. The focus is entirely on commercial ships which are involved in the transport of commodities. The European market is the prime target, but information on all ships throughout the world is used within the model. The ARTEMIS model, and the report by Sjöbris *et al.* (2005), contain more information on the character and emissions behaviour of vessels in the maritime shipping sector than has ever been assessed and presented before.

In the model, emissions can be calculated with reasonable accuracy using a 'simple method' which requires only very limited input information. A 'detailed method' is also defined, and its use will result in better accuracy. In the detailed method, energy consumption and emission factors are allocated to different types of ship, and as a function of vessel size (given as either GT or DWT) and speed. Speed is a crucial input parameter, as the cruise speed determines how much power is needed for operation. The power required is described as a function of vessel size, and defines the emission characteristics of the ship, depending on the type of engine and fuel used. This information is especially of interest when AIS[56] data are available as the basic input when assessing ship movements. Emission factors are given for the most common type of engine for the ship type and speed. Emission factors are also presented for auxiliary engines, and adjustment factors are included for the different types of emission-control equipment that may be installed.

E5.2 The ARTEMIS database

A maritime shipping database was defined in ARTEMIS for use in the development of the emissions model. The database was assembled from several sources, but was primarily based upon the largest available source of information - the world shipping fleet statistics in *Lloyd's Register*. The *Register* contains details of around 145,000 ships, of which approximately 95,000 are in operation. Of the 95,000 in-service vessels in *Lloyd's Register*, the 66,000 built on, or after, 1 January 1980 were selected for further processing. The vessels types included in the database were limited to commercial ships of 100 GT and above. The size of the available database was, however, further limited according to the type of analysis being conducted. For example, for the analysis of fuel consumption the size of the database was reduced to 28,000 vessels, whereas for the analysis of speed and power information was available for more than 50,000 vessels.

All ships are unique, but for practical purposes a classification scheme is required. The system of classification used in *Lloyd's Register* is shown in **Table E-1**, which also provides an indication of the representation of different ship types in European ports, based upon a summary of port calls in Northern Europe for the year 2001. It should be noted that the number of port calls does not describe the total transport activity of the ship type, which is also related to the size of the ship.

The system of classifying ships in the ARTEMIS database followed the scheme used in *Lloyd's Register*, with some slight adjustments. The 12 major ship types used in ARTEMIS are described in **Table E-2**. Although the project has used types which relate to the *Register*, a number of ships are designed for special purposes and have therefore been named in a way which gives a more useful description of the ship's character. For example, ship type can relate directly relate to the type of commodity normally carried, but only in a general manner.

[56] AIS = Automatic Information System, compulsory in Europe from 1 July 2004 on all ships of 300 GT or larger. The system aims to relay as much activity-related information as possible, and to give a continuous update of each individual ship's operation. The ship's identity is disclosed, as well as the previous and next port of destination. An important feature of the AIS-system is the possibility of obtaining a detailed assessment of a ship's fuel consumption and performance using continuously reported information.

Some of the ship types in *Lloyd's Register* are not identified separately in **Table E-2**. These include 'combined ships' (designed to carry either wet or dry bulk cargo) and different types of tanker. Combined vessels are now few in number, and the fleet is diminishing. In ARTEMIS, combined ships are treated as bulk ships, to which they are similar in terms of size, speed, fuel consumption and emissions. All types of tanker (other than gas tankers) are grouped together. The differences between tankers mainly relate to how they are equipped, and the hulls tend to vary only slightly. The speed range is also narrow (generally 13-16 knots). The nature of the cargo imposes special demands on the equipment required onboard, and gas tankers are treated separately as they carry low-density cargo. Ferries are divided into three groups: 'cargo', 'passenger' and 'high-speed'. High-speed ferries are treated according to their DWT, whether they are cargo carrying or not, as the weight governs the speed performance and hence the fuel consumption. Offshore ships and any other types of ship were omitted from the ARTEMIS assessment, as either the frequency of port calls or the number of ships was low.

It is worth noting that the ship type is assigned according to the ship's equipment and the class notation. Ships of the same type may vary substantially in performance. Each ship type was therefore divided into size groups, and each size group was further divided into operational speed levels, as discussed later in the Part. Emission factors were determined as functions of ship type, energy consumption, speed and weight (DWT and/or GT). For each type of ship, characteristic information on size and speed was obtained from *Lloyd's Register*.

Table E-1: The classification scheme in *Lloyd's Register*, and the representation of different ship types in port calls in Northern Europe during 2001.

Ship type	Representation in port calls in Northern Europe (2001)	
	Number	%
Bulk ship	53,363	15.6%
Combination	710	0.2%
Dry cargo	102,508	30.0%
Container	35,712	10.5%
Ro-Ro	57,175	16.8%
Reefer	6,445	1.9%
Passenger ferry	4,940	1.4%
Crude oil tanker	6,122	1.8%
Product tanker	32,229	9.4%
Chemical tanker	26,352	7.7%
Gas tanker	8,450	2.5%
Misc. tanker	139	0.0%
Offshore	280	0.1%
Others	6,847	2.0%
Total	341,272*	100.0%

* It is worth noting that regular ferry services account for approximately 3,200,000 port calls.

Table E-2: Description of ship types in ARTEMIS

Ship type (alternative name)		General description
1	Bulk ship (bulker)	Free-flowing dry bulk of all types and of low value.
2	Dry cargo (general cargo)	All types of unitised cargo (non rolling), free-flowing bulk, project cargo, *etc*. Average ship size about 3,500 DWT, handling smaller quantities - in many cases directly to industries.
3	Container	Traditionally high-value cargo. Containerisation results in a widening of the range of products handled. Mainly palletised and unitised cargo, but can be everything from digital cameras to bags of fertilizer.
4	Ro-Ro	Road vehicles and rolling terminal vehicles carrying unitised cargo or cargo units. Medium-to-high value cargo.
5	Reefer	Refrigerated or temperature-controlled cargo on pallets/hanging or unitised. Mainly food. To a large extent, losing market to container ships.
6	Cargo ferry	Normally a Ro-Ro ship having passenger capacity, usually operating between two ports only.
7	Passenger ferry (non-cargo ferry)	Smaller ship (*e.g.* for servicing islands or crossing rivers) having passenger carrying capacity. Takes various forms, depending on the market. Service speed less than 30 knots.
8	High-speed ferry (fast ferry)	Cargo and passenger ferries with a stated service speed greater than or equal to 30 knots.
9	Tanker	Oil tankers carry crude oil. Product tankers carry various types of refined oil products, and have smaller tanks to carry different products at the same time. Chemical Tankers are built to carry oxidising and hazardous products in smaller, specially coated tanks, and are often found competing in the product tanker market.
10	Gas tanker	LPG and LNG tankers, carrying liquified gas under pressure.
11	Cruise vessel	A ship that carries only passengers.
12	Vehicle carrier	A Ro-Ro ship specially designed for the shipping of new cars. Some larger vessels can handle large, rolling cargoes on a number of decks.

E5.3 Main engine emission factors

The approach adopted in ARTEMIS for determining emission factors was to produce values which reflected vessels which were of a similar type, size and speed, and involved in similar processes. Within ARTEMIS, *Lloyd's Register* was populated with emission data collected from ship engine manufacturers. Registered information was used as the basis for the determination of emission factors. For each ship type and size the following information was obtained from *Lloyd's Register*:

(i) Type of main engine
(ii) Power of main engine
(iii) Types of auxiliary engines
(iv) Power of auxiliary engines
(v) Fuel used
(vi) Cruising speed
(vii) Fuel consumption at cruising speed

A survey was conducted of emission measurements for the types of marine engine currently in use. Emission factors corresponding to specific engines were obtained from tests and trials conducted by manufacturers, and this information was then added to the *Register* for each ship (in the section on engine data). The data were used to determine average emission factors for vessels delivered on, or after, 1980. Where no emission factors had been measured for a specific engine, typical emission factors for the engine type were used. For each ship type, regression analyses were then conducted to determine the relationships between ship type, energy consumption and emissions. In this way ship emissions could be assessed on the basis of ship type and size, with the later stated as either GT or DWT.

From an emissions point of view, vessel speed is essential. However, the speed is not known in all cases. The speed listed in *Lloyd's Register* is the 'service speed', defined as 'the speed which the ship is stated to be capable of maintaining at sea in normal weather and at normal service draught'. The fuel consumption of a ship, expressed in tonnes of fuel per day, may also be listed. The figures are described as being 'stated by the owner or obtained from other reliable sources'. Compared with other vehicles types, ships operate in a very limited number of modes, and most of the ship types have a very narrow speed range. Ships are normally cruising at operational speed when at sea. By including speed in the definition of ship type, it was possible to identify comparable types and rationalise the calculation method. When in port, a ship uses different levels of energy depending on the type of ship and activity in ports.

Sulphur emission factors (per unit of fuel consumed) were derived as a function of the sulphur content of the fuel, and are stated as SO_x. The sulphur content of different fuels was based upon the market survey conducted by ENTEC (2002).

E5.4 Auxiliary engines

Energy is also consumed during a ship's stay in port. Some ships are just hotelling, whereas others use energy for loading and discharging. This has to be modelled for each type of ship. In order to operate on-board electric equipment, and to control thrusters during manoeuvring, most vessels are equipped with additional power, provided by auxiliary engines. In the ARTEMIS model a rough approximation of installed auxiliary engine power can be made based on vessel type and size. Auxiliary engine loads when loading and unloading as a percentage of total installed auxiliary engine power are also considered.

E5.5 Emission control equipment

Information on the effects of exhaust emission-control equipment was also collected and added to the *Register*. Emission-control devices which can be found on ships include oxidation catalysts, selective catalytic reduction (SCR) systems, humid air motors (HAM - in which the inlet air is saturated with warm water), scrubbers, and direct water injection (DWI). These technologies are described in more detail by Sjöbris *et al.* (2005). However, by the end of 2004, the proportion of in-service ships which had been fitted with emission control devices was still relatively low. Sjöbris *et al.* (2005) also list details of 90 ships which had been fitted with such devices, but even these ships do not use the equipment routinely. In the ARTEMIS model, the emission reductions associated with different emission-control systems are defined according to manufacturers' specifications.

E6 ARTEMIS modelling approach

The ARTEMIS model provides two main approaches for determining the fuel consumption and emissions for a particular vessel type. The first approach - the 'simple method' - involves the use of the ship's type and size to look up emission values in a static table. The second approach - the 'detailed method' – can be used if more information is available, and involves the following four steps:

Step 1: Determination of average speed

Step 2: Determination of main engine power output

Step 3: Identification of main engine type

Step 4: Estimation of fuel consumption and emissions

Two further considerations apply to both approaches:

(i) Emissions associated with the effects of auxiliary engines. Energy is also consumed during a ship's stay in port (*e.g.* during loading and unloading), and most vessels are equipped with auxiliary engines to produce additional power. A separate method is presented for calculating the emissions from such engines.

(ii) The effects of emission-control equipment. If emission-control equipment is used on board, the derived emission factors (for main and/or auxiliary engines as appropriate) can be adjusted accordingly.

The two main approaches, and the effects of auxiliary engines and emission control, are described in more detail in the following Sections.

E6.1 Simple method

Average fuel consumption factors per ship type and fuel type are presented in **Table E-3**. Fuel consumption values are presented for marine diesel oil (MDO), marine gas oil (MGO) and residual oil (RO). Overall weighted average values are also given. If the type of fuel is not known, it can either be set a quality that is relevant to the trading area (preferred), or can be inferred from the statistics given in **Table E-3**.

Table E-3: Average fuel consumption factors per ship type and fuel type.

Ship type	Number of ships in database	% of fuel consumption by fuel type			Average fuel consumption (tonnes/day) by fuel type			
		MDO	MGO	RO	MDO	MGO	RO	Overall weighted average
Bulk ship	4,598	73	0	27	30	10	29	30
Combined ship	*1,251*	*51*	*0*	*49*	*44*		*79*	*61*
Dry cargo	75	64	1	35	11	10	18	13
Container	539	83	0	16	67	29	74	68
Ro-Ro	5,135	75	3	22	23	23	37	26
Reefer	355	80	0	20	23		25	23
Cargo ferry	1,867	77	6	18	30	60	49	35
Passenger Ferry	857	76	9	14	7	23	20	10
Tanker (oil)	10,568	44	0	56	31	20	74	56
Tanker (chemical)	408	80	4	16	18	23	26	19
Gas tanker - LNG	674	30	8	62	137	100	108	116
Gas tanker - LPG	1,275	76	2	21	18	18	23	19
Cruise vessel	456	61	7	31	63	205	86	81
Vehicle carrier	266	80	0	19	26	18	38	28
Total	28,324							

Average emission factors per ship type and size are presented in **Table E-4**. These are based on emission factors for individual types of engine reported by the manufacturers. The sample represents 60% of all ships in the database which were constructed in, or after, 1990.

E6.2 Detailed method

By knowing the type of vessel, its size and its service speed, the main engine power output can be estimated based on statistical fits to the values in the database. The type of ship and the main engine power value can then be used to identify the most likely type of engine being used. For the given type of engine, and its power rating, the specific fuel consumption and specific emission factors can then be referenced. These are multiplied by the actual engine power to give hourly and daily emission rates.

Table E-4: Average emission factors per ship type and size (ships ordered/delivered 1990-2006).

	Ship type	Size	g NO_x /DWT/day	g NO_x /GT/day	g CO /DWT/day	g CO /GT/day	g HC /DWT/day	g HC /GT/day	g PM /DWT/day	g PM /GT/day
1	Bulk ship	80,000+ DWT	39	75	1.7	3.2	1.3	2.6	1.1	2.1
		55,000-79,999 DWT	48	90	2.9	5.4	1.8	3.4	1.5	2.9
		10,000-54,999 DWT	73	121	3.5	5.9	3.1	5.1	2.1	3.4
		<10,000 DWT	183	260	3.4	4.9	1.3	1.9	2.8	4.0
		<500 GT	Records not available for ships of this size							
2	Dry cargo	10,000+ DWT	135	184	6.1	8.3	4.6	6.4	3.9	5.2
		<10,000+ DWT	162	217	6.1	8.2	4.3	5.9	2.5	3.3
		<500 GT	Records not available for ships of this size							
3	Container	5,000+ TEU[57]	278	298	12.3	13.2	14.7	15.5	8.8	9.1
		3,000-4,999 TEU	264	308	9.9	11.6	12.5	14.6	7.8	9.0
		1,000-2,999 TEU	243	303	12.1	14.9	10.9	13.4	7.4	9.3
		<1,000 TEU	240	297	10.1	12.4	3.7	4.6	4.2	5.1
		<500 GT	Records not available for ships of this size							
4	Ro-Ro	2,200+ LM[58]	439	249	23.9	14.4	12.4	8.0	9.0	5.3
		<2,200 LM	368	281	13.7	10.6	11.4	9.2	4.7	4.1
		<500 GT	Records not available for ships of this size							
5	Reefer	7,100+ m^3	412	434	18.2	19.2	18.7	18.9	12.5	12.4
		<7,100 m^3	334	300	9.2	8.2	6.9	5.3	3.8	4.1
		<500 GT	Records not available for ships of this size							
6	Cargo ferry	1,300+ LM	1964	361	89.8	17.3	42.7	7.8	23.0	4.4
		<1,300 LM	1806	341	71.4	16.5	44.9	8.8	28.1	5.8
		<500 GT	Records not available for ships of this size							
7/8	Passenger ferry	>500 GT	1249	273	77.9	17.5	35.1	6.5	15.8	2.5
		<500GT	Records not available for ships of this size							
9	Tanker-oil	200,000+ DWT	31	58	1.4	2.7	0.9	1.6	0.9	1.7
		60,000-199,999	46	82	2.6	4.7	1.5	2.8	1.4	2.5
		10,000-59,999 DWT	81	129	3.7	5.9	2.8	4.4	2.4	3.8
		<10,000 DWT	131	190	5.0	72	5.1	7.4	2.5	3.7
		<500 GT	Records not available for ships of this size							
	Tanker-chemical	60,000+ DWT	49	83	3.3	5.6	1.7	2.8	1.7	2.9
		10,000-59999 DWT	96	150	4.7	7.3	2.9	4.5	2.4	3.6
		<10,000 DWT	171	249	6.9	10.3	5.4	7.8	2.6	3.7
		<500 GT	Records not available for ships of this size							
10	Gas tanker	LNG	114	69	9.0	5.4	1.8	1.1	0.0	0.0
		LPG 50,000+ m^3	180	217	7.5	9.0	6.1	7.3	3.4	4.3
		LPG <50,000 m^3	89	105	4.9	5.7	2.7	3.1	2.9	3.5
		<500 GT	Records not available for ships of this size							
11	Cruise vessel	1,000+ low berths[59]	1904	184	199.2	19.7	25.4	2.4	0.0	0.0
		<1,000 low berths	1860	202	59.7	6.8	64.7	7.4	15.0	2.3
		<500 GT	Records not available for ships of this size							
12	Vehicle carrier	4,000+ CEU[60]	321	105	16.4	5.4	9.6	3.2	9.6	3.2
		<4,000 CEU	442	162	16.0	6.1	15.7	5.8	7.0	3.0
		<500 GT	Records not available for ships of this size							

[57] TEU = Twenty-foot Equivalent Units (*e.g.* a 20' container = 1 TEU, a 40' container = 2 TEU). The nominated units for defining the size of container ships.
[58] LM = lane meters. Used to calculate how many trailers a ship can hold. The nominated units for describing trailer and Ro/Ro capacity.
[59] Low berths = nominate way of giving berth (passenger) capacity in cabins. There is also Upper berths capacity giving all available passenger (*i.e.* cargo) berths.
[60] CEU = car equivalent units.

Step 1: Determination of average speed

If the actual service speed of a vessel is not known, it can be estimated based on the vessel's type and size. Values for average ship speed in relation to DWT and GT are shown in **Table E-5** and **Table E-6**.

Table E-5: Average speed per ship type and DWT group.

	Ship type	Average speed (knots) per DWT band							
		<500	<5000	<10,000	<25,000	<50,000	<100,000	<250,000	>250,000
1	Bulk ship	11	12	13	14	15	15	15	14
2	Dry cargo	13	13	14	16	15	15		
3	Container		14	16	19	22	24	25	
4	Ro-Ro	14	16	18	18	20			
5	Reefer		15	19	21	21			
6	Cargo ferry	20	19	22	19	18			
7	Passenger ferry		18	19	23				
8	High-speed ferry	30							
9	Tanker	13	13	13	14	15	15	15	15
10	Gas tanker	17	13	15	16	17	19		
11	Cruise vessel	15	18	21	23				
12	Vehicle carrier	14	16	19	19	19	15		

Table E-6: Average speed per ship type and GT group.

	Ship type	Average speed (knots) per DWT band							
		<500	<5000	<10,000	<25,000	<50,000	<100,000	<250,000	>250,000
1	Bulk ship	12	13	14	15	15	15	14	
2	Dry cargo	12	13	15	17	15	15		
3	Container		14	17	19	22	24	25	
4	Ro-Ro	13	15	16	18	21	22		
5	Reefer	16	16	19	21	21			
6	Cargo ferry	16	18	20	20	23	22		
7	Passenger ferry		26	17	21	23			
8	High-speed ferry	31							
9	Tanker	10	13	14	15	15	15	15	17
10	Gas tanker		13	15	16	17	20	20	
11	Cruise vessel	19	15	17	19	21	22	22	
12	Vehicle carrier	15	15	16	18	19	20		

Step 2: Determination of main engine power output

The power output of the main engine of a vessel can be estimated given its type, size and service speed. In the analysis of the database, statistical fits to the vessel size (both GT and DWT) and power values in the database yielded functions giving the probable main engine power output. Each type of vessel was then sorted by operating speed in integer values. Some examples of the fitted functions (for large bulk ships) are shown in **Figure E-1**.

Trends which could be considered to be representative for each type of ship, such as those based upon a large sample size and having a good statistical fit (high R^2 value), were used to calibrate the curves for speed samples which were based on just a few observations. It was not possible to take account of all the parameters governing the relationships between the ship type, its size, and the power needed to produce a given speed, as all the required information was not registered.

For each type of vessel, the relationships between size and main engine power (ME) are stated in the following forms:

$ME\ (kW) = k * GT^{\wedge n}$ for gross tonnage

and

$ME\ (kW) = k * DWT^{\wedge n}$ for deadweight

The coefficients ***k*** and ***n*** are constants for each vessel type at a given speed. Values for ***k*** and ***n*** for the various types of ship in the model are given in **Table E-7** to **Table E-20**.

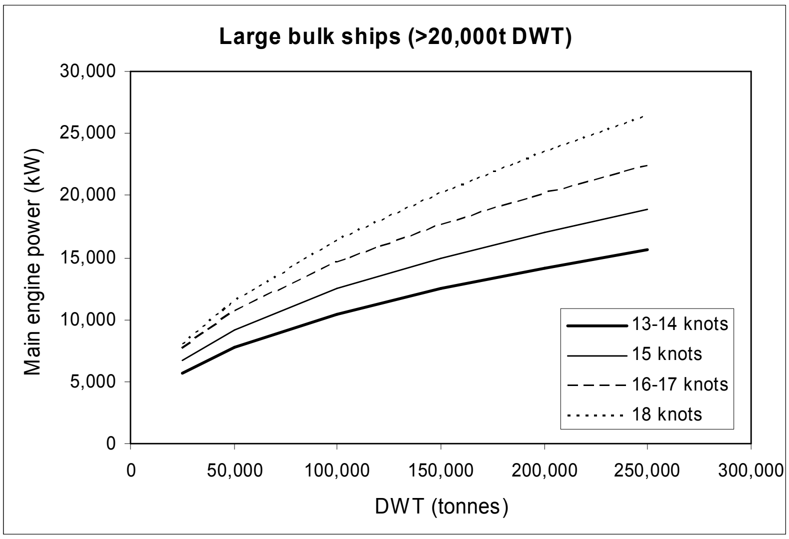

Figure E-1: Relationships between vessel size and main engine power for different speeds (bulk ships >20,000 DWT).

Table E-7: Main engine power coefficients for bulk ships.

ME as a function of GT by speed			ME as a function of DWT by speed					
			<20,000 DWT			>20,000 DWT		
Speed (kts)	*k*	*n*	Speed (kts)	*k*	*n*	Speed (kts)	*k*	*n*
9-11	45.838	0.4169	10	64.752	0.3503	13-14	69.921	0.4351
12	38.764	0.5052	11	52.842	0.4044	15	69.407	0.4510
13-14	53.396	0.4852	12	44.177	0.4478	16-17	70.175	0.4638
15	60.935	0.4871	13	37.042	0.4879	18	41.059	0.5201
16-17	65.748	0.4963	14	27.429	0.5329			
			15	27.490	0.5466			
			16	28.321	0.5550			

Table E-8: Main engine power coefficients for dry cargo ships.

ME as a function of GT by speed			ME as a function of DWT by speed		
Speed (kts)	*k*	*n*	Speed (kts)	*k*	*n*
<8	4.3879	0.6985	<8	0.9607	0.8323
8	7.3138	0.6266	8	2.3159	0.7323
9	9.6173	0.5931	9	3.5786	0.6902
10	13.340	0.5544	10	6.6358	0.6276
11	17.355	0.5408	11	12.425	0.5663
12	19.414	0.5602	12	15.351	0.5678
13	20.299	0.5773	13	18.997	0.5646
14	22.556	0.5828	14	29.680	0.5305
15	27.881	0.5725	15	44.083	0.5012
16	34.534	0.5638	16	44.297	0.5151
17	55.548	0.5275	17	41.548	0.5362
18	57.296	0.5364	18	39.941	0.5548
19	105.58	0.4849	19	39.405	0.5727
20	156.55	0.4578	20	102.31	0.4903
21	344.98	0.3915	21	218.13	0.4338

Table E-9: Main engine power coefficients for container vessels.

ME as a function of GT by speed			ME as a function of DWT by speed		
Speed (kts)	***k***	***n***	Speed (kts)	***k***	***n***
			<16	3.8556	0.7612
16	44.842	0.5408	16	19.536	0.6089
17	77.312	0.4946	17	29.4	0.5796
18	104.78	0.4774	18	76.086	0.4941
19	132.25	0.4644	19	160.65	0.433
20	142.72	0.4679	20	293.5	0.4071
21	186.03	0.4528	21	295.93	0.4001
22	155.96	0.4813	22	384.24	0.3892
23	82.339	0.5546	23	321.78	0.4214
24	53.756	0.605	24	164.05	0.4972
25	34.97	0.6562	25	72.141	0.5869
26	25.002	0.6975	26	55.869	0.6212

Table E-10: Main engine power coefficients for Ro-Ro vessels.

ME as a function of GT by speed			ME as a function of DWT by speed		
Speed (kts)	***k***	***n***	Speed (kts)	***k***	***n***
<9	25.384	0.4838	<9	27.029	0.4494
9	27.919	0.4832	9	21.336	0.497
10	46.212	0.4286	10	24.417	0.5043
11	30.412	0.5068	11	27.07	0.5192
12	47.933	0.4667	12	41.59	0.4861
13	75.99	0.4279	13	63.995	0.4536
14	99.983	0.4118	14	74.333	0.4527
15	115.36	0.41	15	75.937	0.4693
16	130.25	0.4159	16	72.454	0.4949
17	140.2	0.4283	17	71.11	0.5169
18	189.44	0.4142	18	101.46	0.497
19	192.26	0.4281	19	182.05	0.4512
20	316.94	0.3901	20	308.55	0.4106
21	664.6	0.3268	21	449.88	0.3841
22	1179.4	0.2794	22	697.02	0.3493
23	1687.9	0.2534	23	1084.2	0.3157

Table E-11: Main engine power coefficients for reefer ships.

ME as a function of GT by speed						ME as a function of DWT by speed		
<5,000 GT			>5,000 DWT					
Speed (kts)	***k***	***n***	Speed (kts)	***k***	***n***	Speed (kts)	***k***	***n***
10-11	42.397	0.4141	15	44.425	0.5122	10	5.8621	0.6831
12-13	30.491	0.5169	16	55.156	0.5102	11	6.3304	0.6986
14-15	42.751	0.5128	17	111.88	0.4488	12	10.961	0.6392
16-17	44.127	0.5472	18	175.92	0.4094	13	24.182	0.5546
18-19	204.64	0.3967	19	217.46	0.3974	14	38.529	0.5122
			20	206.93	0.4132	15	34.009	0.5437
			21	239.9	0.4087	16	50.839	0.5157
			22	185.23	0.4497	17	72.331	0.4917
			23	155.77	0.48	18	98.164	0.4714
			24	80.229	0.5642	19	112.03	0.4697
						20	166.41	0.4376
						21	172.15	0.4488
						22	104.09	0.5174

Table E-12: Main engine power coefficients for cargo ferries.

ME as a function of GT by speed			ME as a function of DWT by speed		
Speed (kts)	***k***	***n***	Speed (kts)	***k***	***n***
9-13	28.624	0.5405	9-13	150.56	0.3227
14-18	38.518	0.5738	14-18	166.08	0.454
19-24	84.472	0.5393	19-24	290.14	0.4739
25-29	67.39	0.6286	25-29	275.13	0.577

Table E-13: Main engine power coefficients for passenger ferries.

ME as a function of GT by speed			ME as a function of DWT by speed		
Speed (kts)	***k***	***n***	Speed (kts)	***k***	***n***
9-13	19.208	0.5796	9-13	93.195	0.3982
14-18	140.32	0.3801	14-18	299.51	0.3402
19-24	69.114	0.554	19-24	215.61	0.5162
25-29	87.564	0.5742	25-29	715.1	0.2699

Table E-14: Main engine power coefficients for passenger ferries.

ME as a function of GT by speed			ME as a function of DWT by speed		
Speed (kts)	***k***	***n***	Speed (kts)	***k***	***n***
30-34	47.013	0.7052	30-35	152.9	0.7392
35-38	54.705	0.7139	36-39	304.49	0.6886
39-41	55.564	0.7247	40+	363.55	0.6746
42-44	57.507	0.735			
45+	61.422	0.7442			

Table E-15: Main engine power coefficients for tankers (GT).

ME as a function of GT by speed					
<5,000 GT			>5,000 GT		
Speed (kts)	***k***	***n***	Speed (kts)	***k***	***n***
<10	12.273	0.5781	13	43.715	0.5095
10	30.878	0.4703	14	43.715	0.5095
11	51.849	0.4298	15	52.8	0.5082
12	44.005	0.4762	16	64.108	0.5044
13	51.742	0.4763	17	79.34	0.4952
14	53.269	0.4885			
15	52.8	0.5082			

Table E-16: Main engine power coefficients for tankers (DWT).

ME as a function of DWT by speed								
<10,000 DWT			10,000-60,000 DWT			>60,000 DWT		
Speed (kts)	***k***	***n***	Speed (kts)	***k***	***n***	Speed (kts)	***k***	***n***
<9	13.547	0.5219	13	28.353	0.5237	14	50.322	0.4725
9	16.156	0.5175	14	37.544	0.5046	15	39.921	0.5025
10	16.872	0.5198	15	47.845	0.4911	16	73.777	0.4657
11	17.966	0.5344	16	65.161	0.4793	17	105.71	0.4468
12	15.864	0.571	17	65.057	0.496			
13	19.463	0.5656						
14	19.535	0.5787						
15	30.294	0.5443						

Table E-17: Main engine power coefficients for gas tankers (LNG).

ME as a function of GT by speed			ME as a function of DWT by speed		
Speed (kts)	***k***	***n***	Speed (kts)	***k***	***n***
<18	23.375	0.5946	<18	11.608	0.6707
18	227.47	0.3925	18	67.328	0.5164
19	386.21	0.3556	19	96.644	0.4902
20	604.05	0.3252	20	271.12	0.4043
21	825.44	0.3069	21	325.32	0.3948

Table E-18: Main engine power coefficients for gas tankers (LPG).

ME as a function of GT by speed			ME as a function of DWT by speed		
Speed (kts)	***k***	***n***	Speed (kts)	***k***	***n***
10	48.024	0.391	10	20.591	0.5253
11	78.635	0.3614	11	32.046	0.4856
12	71.16	0.4028	12	37.728	0.4846
13	60.473	0.4472	13	41.119	0.4929
14	62.701	0.4632	14	43.697	0.5003
15	74.578	0.4636	15	52.035	0.4911
16	95.104	0.4501	16	70.171	0.4712
17	135.15	0.4269	17	70.335	0.4815
>17	144.75	0.4308	>17	57.889	0.5111

Table E-19: Main engine power coefficients for cruise vessels.

ME as a function of GT by speed			ME as a function of DWT by speed		
Speed (kts)	***k***	***n***	Speed (kts)	***k***	***n***
<12	3.5852	0.7752	<12	41.305	0.5141
12-13	8.0077	0.6995	12-13	75.18	0.4892
14-15	10.974	0.6852	14-15	134.28	0.4553
16-17	17.658	0.6516	16-17	175.73	0.4661
18-19	20.572	0.6528	18-19	111.4	0.5854
20-21	30.969	0.6306	20-21	123.02	0.6091
22-23	41.075	0.6257	22-23	91.224	0.696

Table E-20: Main engine power coefficients for vehicle carriers.

ME as a function of GT by speed			ME as a function of DWT by speed		
Speed (kts)	***k***	***n***	Speed (kts)	***k***	***n***
			<14	38.059	0.4945
14	56.46	0.454	14	71.328	0.4563
15	118.43	0.3946	15	141.91	0.4007
16	210.96	0.3492	16	251.55	0.3546
17	361.19	0.3076	17	362.08	0.3293
18	629.84	0.2654	18	507.01	0.3086
19	1187.5	0.2156	19	756.85	0.2826
20	2058.7	0.1787	20	1250.2	0.246
21			21	1528.4	0.2381

Step 3: Identification of main engine type

The most likely type of main engine for each type is determined on the basis of probability. When the probable power output of the main engine has been determined, it is possible to asses what type of engine the ship has using **Table E-21**, which gives the distribution of different engine types per ship type.

For example, it can be seen that the vast majority of engines in bulk ships are two-stroke diesel, except for some of the less powerful ones which are of the four-stroke type. Steam reciprocating engines can be found on smaller bulk ships, but rarely on vessels built during the last 15 years. Some larger, predominately older, engines are of the steam turbine type. Dry cargo ships are usually small vessels, and the most common type of engine is the four-stroke diesel. Two-stroke diesel engines are more common in larger vessels. Steam engines are rare in dry cargo vessels, especially in more modern ships. Larger container vessels are more likely to have two-stroke diesel engines than smaller ones, although four-stroke engines are more common in the 5-10,000 kW power range compared with bulk and dry cargo ships.

Most Ro-Ro vessels are equipped with four-stroke diesel engines. This can partly be attributed to the restrictions on engine room height and space in the aft part of the ship due to ramp arrangements. The use of several four-stroke engines instead of one large two-stroke engine is also common, and allows for greater flexibility in operation. As for other types of vessel, larger reefers are more likely to have two-stroke diesel engines than smaller reefers.

The vast majority of cargo ferries and passenger ferries have four-stroke diesel engines. Frequent departures, manoeuvring in ports, and varying modes and conditions of operation call for flexibility, with several main engines to optimise the power output, and often double propulsion systems. The data for passenger ferries with main engine power output higher than 5,000 kW the data must be viewed with caution, as there are few such ferries in service. The majority of high-speed ferries have four-stroke diesel engines, especially smaller vessels. Larger ferries, and ferries with a high service speed, can be equipped with gas turbines or a combination of gas turbines and four-stroke diesel engines. One reason for not using two-stroke engines is weight of the machinery, which renders it unsuitable for high-speed vessels; four stroke engines have a higher power output per unit weight, and demand less space.

Generally, small tankers are equipped with four-stroke diesel engines and large tankers with two-stroke diesel engines. The majority of the largest (mostly older) ships are equipped with steam turbines. Most cruise vessels are equipped with four-stroke diesel engines, but there are no clear relations between total installed main engine power output and engine type, except that the only gas turbine engine sets are found in vessels with a power output of 25,000 kW or more. Most vehicle carriers are equipped with two-stroke diesel engines, except the smaller vessels. The data for largest engine group (power output > 25,000 kW) should again be viewed with caution, as there are only data for two ships.

Step 4: Estimation of fuel consumption and emissions

For the given type of engine and its power rating, the specific fuel consumption and specific emission factors are then determined. **Table E-22** gives the specific fuel consumption (SFC) and emission factors for eight different diesel engine power ratings, and for both two-stroke and four-stroke engines. These values are then multiplied by the actual engine power to give hourly emission rates.

Table E-21: Number of ships by main engine type per main engine power output for each vessel type.

	Ship type	Main engine type	Number of ships by ME power output (kW)							
			<500	500-2,500	2,500-5,000	5,000-7,500	7,500-10,000	10,000-15,000	15,000-25,000	>25,000
1	Bulk ship	Steam –	0 (0%)	34 (7%)	8 (1%)	0 (0%)	0 (0%)	0 (0%)	0 (0%)	0 (0%)
		Steam – turbine	0 (0%)	7 (1%)	18 (2%)	51 (2%)	11 (0%)	28 (1%)	59 (9%)	2 (15%)
		Diesel – four	78 (96%)	353 (81%)	107 (17%)	136 (6%)	63 (2%)	30 (2%)	2 (0%)	1 (7%)
		Diesel – two	3 (3%)	39 (9%)	476 (78%)	1966	2432	1380	543 (89%)	10 (76%)
2	Dry cargo	Steam –	20 (0%)	139 (2%)	3 (0%)	1 (0%)	0 (0%)	0 (0%)	0 (0%)	0 (0%)
		Steam – turbine	0 (0%)	1 (0%)	99 (2%)	35 (1%)	19 (1%)	29 (6%)	10 (16%)	0 (0%)
		Diesel – four	1867	5466	1210 (35%)	297 (15%)	91 (7%)	53 (12%)	4 (6%)	0 (0%)
		Diesel – two	369 (16%)	1237	2056 (61%)	1549	1031	347 (80%)	45 (76%)	2 (100%)
3	Container	Steam – turbine	0 (-)	0 (0%)	0 (0%)	29 (7%)	0 (0%)	17 (3%)	35 (4%)	35 (2%)
		Diesel – four	0 (-)	78 (88%)	118 (48%)	140 (36%)	121 (33%)	24 (4%)	24 (3%)	7 (0%)
		Diesel – two	0 (-)	10 (11%)	123 (51%)	218 (56%)	239 (66%)	504 (92%)	736 (92%)	1169
4	Ro-Ro	Steam – turbine	0 (0%)	0 (0%)	0 (0%)	4 (2%)	0 (0%)	0 (0%)	8 (8%)	1 (10%)
		Diesel – four	55 (93%)	234 (87%)	138 (71%)	148 (80%)	50 (72%)	69 (69%)	55 (58%)	9 (90%)
		Diesel – two	4 (6%)	33 (12%)	55 (28%)	31 (16%)	19 (27%)	31 (31%)	31 (32%)	0 (0%)
5	Reefer vessels	Steam – turbine	0 (0%)	0 (0%)	0 (0%)	0 (0%)	1 (0%)	0 (0%)	0 (0%)	0 (-)
		Diesel – four	25 (86%)	242 (83%)	75 (31%)	33 (12%)	6 (3%)	32 (15%)	0 (0%)	0 (-)
		Diesel – two	4 (13%)	48 (16%)	164 (68%)	234 (87%)	191 (96%)	169 (84%)	25 (100%)	0 (-)
6	Cargo ferry	Steam –	1 (1%)	12 (2%)	1 (0%)	0 (0%)	0 (0%)	0 (0%)	0 (0%)	0 (0%)
		Steam – turbine	0 (0%)	0 (0%)	4 (1%)	7 (3%)	3 (2%)	6 (2%)	3 (1%)	2 (2%)
		Gas turbine	0 (0%)	0 (0%)	1 (0%)	0 (0%)	0 (0%)	0 (0%)	0 (0%)	0 (0%)
		Diesel – four	83 (90%)	443 (79%)	166 (68%)	140 (65%)	109 (75%)	152 (74%)	180 (93%)	91 (96%)
		Diesel – two	8 (8%)	99 (17%)	72 (29%)	66 (30%)	32 (22%)	46 (22%)	9 (4%)	1 (1%)
7	Passenger ferry	Steam –	3 (1%)	11 (2%)	0 (0%)	1 (5%)	0 (0%)	0 (0%)	0 (0%)	0 (-)
		Steam – turbine	0 (0%)	1 (0%)	0 (0%)	1 (5%)	0 (0%)	0 (0%)	0 (0%)	0 (-)
		Gas turbine	0 (0%)	0 (0%)	0 (0%)	1 (5%)	0 (0%)	0 (0%)	0 (0%)	0 (-)
		Diesel – four	179 (92%)	431 (87%)	92 (87%)	7 (38%)	1 (100%)	12 (85%)	7 (100%)	0 (-)
		Diesel – two	12 (6%)	49 (9%)	13 (12%)	8 (44%)	0 (0%)	2 (14%)	0 (0%)	0 (-)
8	High-speed ferry	Gas turbine*	0 (-)	0 (0%)	3 (1%)	33 (48%)	10 (24%)	6 (28%)	3 (6%)	9 (16%)
		Diesel – four	0 (-)	185 (97%)	268 (95%)	33 (48%)	31 (75%)	15 (71%)	41 (93%)	46 (82%)
		Diesel – two	0 (-)	5 (2%)	10 (3%)	2 (2%)	0 (0%)	0 (0%)	0 (0%)	1 (1%)
9	Tanker	Steam – reciprocating	4 (0%)	17 (0%)	1 (0%)	0 (0%)	0 (0%)	0 (0%)	0 (0%)	0 (0%)
		Steam – turbine	0 (0%)	1 (0%)	2 (0%)	91 (9%)	13 (1%)	227 (16%)	333 (28%)	260 (56%)
		Diesel – four stroke	473 (88%)	1945 (87%)	442 (40%)	107 (11%)	63 (5%)	63 (4%)	8 (0%)	13 (2%)
		Diesel – two stroke	59 (11%)	268 (12%)	643 (59%)	748 (79%)	1074 (93%)	1117 (79%)	823 (70%)	189 (40%)
10	Gas tanker (LNG)	Steam – turbine	0 (0%)	0 (0%)	0 (0%)	3 (3%)	2 (2%)	7 (6%)	57 (71%)	86 (100%)
		Diesel – four	0 (0%)	2 (0%)	0 (0%)	0 (0%)	0 (0%)	0 (0%)	0 (0%)	0 (0%)
		Diesel – two	0 (0%)	0 (0%)	1 (0%)	0 (0%)	0 (0%)	0 (0%)	0 (0%)	0 (0%)
	Gas tanker (LPG)	Steam – turbine	0 (0%)	0 (0%)	0 (0%)	1 (1%)	0 (0%)	1 (0%)	0 (0%)	0 (0%)
		Diesel – four	22 (84%)	357 (82%)	103 (44%)	15 (19%)	2 (2%)	1 (0%)	2 (2%)	0 (0%)
		Diesel – two	4 (15%)	76 (17%)	126 (54%)	59 (75%)	78 (95%)	104 (92%)	21 (26%)	0 (0%)
11	Cruise vessel	Steam –	0 (0%)	2 (4%)	0 (0%)	0 (0%)	1 (5%)	0 (0%)	0 (0%)	0 (0%)
		Steam – turbine	0 (0%)	0 (0%)	2 (4%)	5 (13%)	4 (22%)	6 (14%)	14 (23%)	8 (7%)
		Gas turbine*	0 (0%)	0 (0%)	0 (0%)	0 (0%)	0 (0%)	0 (0%)	0 (0%)	18 (17%)
		Diesel – four	5 (71%)	40 (81%)	27 (61%)	14 (38%)	6 (33%)	25 (60%)	29 (48%)	76 (74%)
		Diesel – two	2 (28%)	7 (14%)	15 (34%)	17 (47%)	7 (38%)	10 (24%)	17 (28%)	0 (0%)
12	Vehicle carrier	Diesel – four	0 (-%)	26 (89%)	32 (38%)	14 (28%)	21 (23%)	19 (11%)	7 (10%)	2 (100%)
		Diesel – two	0 (-%)	3 (10%)	51 (61%)	35 (71%)	68 (76%)	152	57 (89%)	0 (0%)

* Including diesel and gas.

Table E-22: Engine specific fuel consumption and emissions for diesel engines, based on engine type and size.

Main engine power (kW)	Engine stroke	SFC (g/kWh)	NO_x (g/kWh)	CO (g/kWh)	HC (g/kWh)	PM (g/kWh)
<500	2	N/A	16.24	0.84	0.45	N/A
<500	4	186.71	12.23	1.30	0.61	0.36
500-2,500	2	N/A	16.37	0.90	0.43	0.40
500-2,500	4	193.43	11.59	0.92	0.55	0.19
2,500-5,000	2	210.00	16.05	0.56	0.42	0.50
2,500-5,000	4	186.97	11.94	0.51	0.32	0.20
5,000-7,500	2	175.00	18.14	0.67	0.52	0.50
5,000-7,500	4	183.93	12.86	0.54	0.23	0.19
7,500-10,000	2	175.00	16.80	0.87	0.47	0.50
7,500-10,000	4	183.49	12.73	0.53	0.24	0.20
10,000-15,000	2	170.00	15.56	0.91	0.47	0.50
10,000-15,000	4	181.28	13.15	0.59	0.30	0.20
15,000-25,000	2	170.00	16.71	0.80	0.44	0.50
15,000-25,000	4	181.30	12.94	0.61	0.26	0.20
>25,000	2	167.00	15.24	0.60	0.22	0.50
>25,000	4	178.66	12.80	0.93	0.23	0.22

Emissions of sulphur are derived from the sulphur content of the fuel oil, and are stated as SO_x. The sulphur content of three different fuels is shown in **Table E-23**.

Table E-23: Sulphur content of fuels (ENTEC, 2002).

Fuel	Sulphur content (%)*
Marine diesel oil (MDO)	1.0
Marine gas oil (MGO)	0.2
Residual oil (RO)	2.0

* values will vary in the market

It is assumed that that all sulphur present in the fuel is burnt to SO_2. For example, if marine gas oil contains 0.2% sulphur, the SO_2 emission per tonne of fuel burnt is given by:

$$SO_2 \text{ (kg/tonne fuel)} = [1000*0.2/100] * [M_r(SO_2)/A_r(S)]$$

$$= 0.2*(64/32)$$

$$= 0.4 \text{ kg/tonne fuel}$$

Where $M_r(SO_2)$ is the relative molecular mass of SO_2, and $A_r(S)$ is the relative atomic mass of sulphur.

If the fuel grade is not known it can be estimated using data from the area of operation, as certain trading areas have tougher restrictions on sulphur content than others. More specific information regarding fuel quality and usage can be found in ENTEC (2002). Emissions of carbon dioxide (CO_2) relate directly to the fuel consumption, and are taken to be 3.2 times the amount of fuel in tonnes.

E6.3 Emissions from auxiliary engines

A rough approximation of installed auxiliary engine power (***AE***) can be made using the equation:

$$AE \text{ (kW)} = k*(GT/DWT)^{\wedge}n$$

Where ***k*** and ***n*** are constants for different ship type, and are given in **Table E-24**. These relationships are based on reliable data from 3,791 ships.

Table E-24: Auxiliary engine power based on vessel type and size.

Ship type	DWT/GT	*k*	*n*
Bulk ship	DWT	35.312	0.3603
Dry cargo	DWT	0.7476	0.7796
Container	DWT	0.5504	0.8637
Ro-Ro	GT	1.347	0.7512
Reefer	DWT	0.4827	0.9375
Cargo ferry	GT	1.655	0.7658
Passenger ferry	GT	1.13	0.8123
Tanker (oil)	DWT	9.9262	0.703
Tanker (chemical)	DWT	5.5294	0.5863
Gas tanker (LNG)	DWT	0.0047	1.2147
Gas tanker (LPG)	DWT	18.043	0.5057
Cruise vessel (mechanical drive)	GT	0.9341	0.9482
Cruise vessel (electric drive)	GT	0.0142	1.0059
Vehicle carrier	GT	0.4916	0.8399

The size-power relationship for high-speed ferries is based on that for cargo and passenger ferries. The relationship between size (DWT) and installed auxiliary engine power for tankers depends upon the type of tanker. Chemical and product tankers tend to have several small tanks, and the power needed to operate pumps is different to that for oil tankers, which have fewer and larger tanks. However, during the analysis of the database it was not possible to distinguish between product and crude oil tankers, but only between chemical and oil tankers. Hence, the results for tankers are split into chemical tankers and oil tankers. Cruise vessel auxiliary engine power depends upon whether a ship is equipped with a traditional diesel engine or a diesel–electric propulsion system.

Table E-25 shows the auxiliary engine loads when loading and unloading as a percentage of total installed auxiliary engine power.

Table E-25: Average power required for auxiliary engines* (Flodström, 1997).

Ship type	Power required as % of total installed auxiliary engine power	
	Loading/unloading	Lay time
Bulk ship	32%	21%
Dry cargo	33%	27%
Ro-Ro	41%	25%
Tankers	62%	19%
Vehicle carrier	37%	18%
All vessels	43%	21%

* Tanker Loading/unloading figure applies for unloading only. Lay-time applies to loading.

The power value from **Table E-24** is then multiplied by the value in **Table E-25** to give the power used during a specific type of operation. Emissions from auxiliary engines are then calculated using the relevant emission factors from **Table E-22**. It is often difficult to know how many auxiliary engines are installed in a given vessel. However, the auxiliary engine power is very seldom greater than 2.5 MW, and is normally at least 2.25 times greater than the power required for an operation. Most modern ships use shaft generators for power supply when steaming, and the power supply needed for auxiliary engines is marginal in relation to that required for propulsion. The operation of auxiliary engines *en route* is therefore not taken into account.

E6.4 Emission-control equipment

If emission-control equipment is fitted to a vessel, then any emission values calculated to this point need to be adjusted to take its effect into account. The adjustments are applied to the emission source which is treated, and in some cases this may only be the auxiliary engines. In the ARTEMIS model, the emission reduction from different emission-control systems is defined according to manufacturers' specifications, as shown in **Table 5-26**. If an additive is required, then this is specified.

Table E-26: Reduction factors for emission -control equipment.

System	Change in emissions						Comments
	NO_x	HC	CO	PM	SO_x	NH_3	
SCR	-95%		+50%	-0-20%		+0,1 g/kWh	Proven technique which does not affect the engine. Affected by the level of sulphur.
SCR + oxidiser	-95%	-80%*	-70%*	-1-20%		+0,1 g/kWh	Proven technique which does not affect the engine. Additive: urea 40% solution, 1.5 lit/kg NO_x.
HAM	-70%	+20%					Water/sea water technique under development. Affects engine. Use of water amounts to 10 times the fuel consumption.
DWI	-60%						Technique under development. Affects engine, and results in an increase in fuel consumption.
Scrubber				-80%	-90%		For small engines, and still under development. Additive: Sea water.

* With oxidiser

E7 Example calculation

An example is given below of how to calculate the emissions from a vessel having a specific identity. The example shows how emissions can be estimated using only limited vessel data.

Ship identity = 3,309 DWT, dry cargo ship

Using the simple method, a quick estimation of the fuel consumption can be obtained from **Table E-3**. According to **Table E-3**, it is most likely that a dry cargo ship will be running on marine diesel oil, and the average fuel consumption value is therefore 11 tonnes/day. Emissions can be estimated using the values in **Table E-4**. This results in the following emission factors and emission rate for this vessel:

Pollutant	Emission factor per DWT for ship type (g/DWT/day)	Emission rate for ship (kg/day)
NO_x	162	536.1
CO	6.1	20.2
HC	4.3	14.2
PM	2.5	8.3

To use the detailed method, the vessel speed and main engine power are also required. Following the steps of the method:

Step 1: Estimation of average speed. From **Table E-5**, the typical speed for a dry cargo ship of between 500 and 5,000 DWT is 13 knots.

Step 2: Estimation of power output. From **Table E-8** the probable ME power output for dry cargo ships travelling at 13 knots is 1,845 kW (=18,997*3309^0.5646).

Step 3: Identification of main engine type. For dry cargo ships, **Table E-21** indicates that the main engine type for the estimated power output (500-2,500 kW) is a four-stroke diesel engine.

Step 4: Estimation of fuel consumption and emissions. The fuel consumption depends on the engine's specific fuel consumption (in g/kWh), which can be obtained from Table **E-22**. For the above vessel, with a four-stroke engine of 1,845 kW, the following data are obtained:

	g/kWh	kg/h	kg/day
SFC	193.43	356.9	8,600
NO_x	11.59	21.4	500
CO	0.92	1.7	40.7
HC	0.55	1.0	24.5
PM	0.19	0.35	8.39

SO_x emissions, CO_2 emissions, emissions due to the use of auxiliary engines, and the effects of emission control equipment are estimated using the methods described.

E8 Uncertainties

The use of a statistical approach to estimate the emission behaviour of a ship is naturally more reliable when the ship is close to the centre of the total population density, and for the majority of ships the level of confidence in the estimation is high. However, there will always be ships of special design which do not fit easily into the modelling approach. The fuel consumption and emission estimates for such vessels are likely to be less robust.

The ARTEMIS method is based upon typical service speeds and main engine power for ships of given types. As individual ships are unique, have a certain service speed, a certain load condition, and travel in a range of weather conditions. Each of these factors can affect the power requirement, and there will always be some uncertainty in the emission factors in relation to such specific applications.

E9 Conclusions and recommendations

The quantification of emissions from maritime shipping can still be regarded as being in its initial stages. In the ARTEMIS maritime shipping report, Sjöbris *et al.* (2005) present a large amount of information to be used for calculating ship emissions under all normal states of operation. The report also presents emission factors to be applied to ships fitted with emission-control equipment, as well as a variety of information that can be useful depending on the type of assessment that is of interest. The intention is to produce an accurate estimate of emissions, based on information that is normally presented when ships call ports.

Activity data

- Useful, stable and reliable activity data are required. The current standard is not acceptable for some types of application, such as the evaluation of trends and development in maritime shipping emissions.
- Article 4 of Commission Decision 2001/423/EC states that ‘the highest level of detail in which (statistical) data may be published or disseminated is the level of port to and from maritime coastal area’. This effectively means that these data cannot used assessments at the level of detail demanded by the Commission.
- At present, the most technically sophisticated, inclusive and reliable source of activity data is the AIS. Continuous information on a ship’s speed, position and heading, as well as weather conditions will make it possible to estimate the power used and the ship’s fuel consumption. The logging of exact routes of will also allow emissions to be assessed in specific sensitive areas. However, the main increase in the quality of predictions will come from the improved reliability of shipping movements and vessel identity.

Emission factors and modelling

- Emission factors must still to be added to existing databases as external information.
- The ARTEMIS model provides two main approaches for determining the fuel consumption and emissions for a particular vessel type. The first approach - the ‘simple method’ - involves the use of the ship’s type and size to look up emission values in a static table. The second approach - the ‘detailed method’ – can be used if more information is available, and also involves average speed, the main engine power output and the main engine type. Two further considerations apply: emissions associated with the effects of auxiliary engines in port, and the effects of emission-control equipment.
- The model provides emission factors for ‘typical’ vessels and conditions For more thorough assessments a more accurate result is only achieved by going into a register to obtain more exact information of the individual ship, such as, fuel consumption at service speed and type of engine and to obtain the quality of fuel used from the ship.
- When restrictions are introduced on emissions[61] the accuracy in the emissions will become higher as control systems will give emissions limits. These limits have to be monitored in some way. Having such monitoring system will assist the engineers of the vessels to tune in the engines. It will thus not be a function of the condition of the engine or how the chief engineer of the ship tunes the engine that guides the emissions.

[61] Annex VI of MARPOL 73/78, the International Convention for the Prevention of Marine Pollution from Ships, requires all ships of 400 GRT or above to obtain an International Air Pollution Prevention certificate. The Annex entered into force on 19 May 2005, and will have an immediate effect on ships constructed on or after that date. Annex VI also requires diesel engines to carry individual certificates with regard to NO_x emissions.

- The outlook for the near future is very positive, and systems will soon be available that can assess emissions automatically without violating the integrity of ship operators or ports.
- Following the entry into force of Annex VI of MARPOL, several Member States submitted a request to the International Maritime Organisation (IMO) for changes to the ship emissions standards. These proposals will be discussed in due course and will need to be fully justified if they are to be adopted by the IMO. Moreover, the Council of Ministers has concluded that the Community should adopt its own measures to reduce NO_x emissions from EU-flagged ships if progress is not forthcoming at the IMO. Given this, it is likely that there will be a requirement to analyse in more detail possible measures to reduce atmospheric emissions from maritime sources.

E10 References

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PART F: AIR TRANSPORT

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F1 Introduction

This Part of the Report presents the work conducted in ARTEMIS on emissions from air transport. More detailed information can be obtained from the report by Kalivoda and Bukovnik (2005). The basic objectives of the work were to close the gaps between the emissions research community and the users of methodologies for compiling emission inventories, and to develop an improved air transport emission database and model. Emphasis was placed on the amalgamation of existing data, although various new measurements were also conducted.

The EMEP/CORINAIR Emission Inventory Guidebook provides three methods for estimating emissions from air transport[62] - a very-simple methodology, a simple methodology, and a detailed methodology. All three methods are top down approaches, based on fuel sales statistics. Four different classes of air traffic activity are taken into account:

- Domestic airport traffic (Landing Take Off (LTO)-cycle < 1000 m altitude).
- International airport traffic (LTO-cycle < 1000 m altitude).
- Domestic cruise traffic (> 1000 m altitude).
- International cruise traffic (> 1000 m altitude).

The Guidebook has recently been revised and incorporates the detailed methodology in accordance with that proposed in COST 319 (European Commission, 1999b), the emission factors taken from ANCAT[63]/EC2 (fuel consumption and NO_x) and the MEET (CO and HC) methodologies (European Commission, 1999a). Data are available for a basic split between ground-related emissions under 3,000 feet (or approximately 1000 m) and cruise-related emissions above 3000 feet. A further distinction has to be made to take account of aircraft operation, which leads to the following six categories:

- Taxi-out.
- Take-off.
- Ground-related climb to 3000 feet.
- Cruise-related climb from 3000 feet to cruise altitude, cruise, cruise-related descent from cruise altitude to 3,000 feet.
- Final approach from 3000 feet and landing.
- Taxi-in.

Knowledge of aircraft emission characteristics has improved in recent years, mainly through European Union research projects such as POLINAT or AEROCERT, but limited practical use has been made of this information in national inventories and international reporting mechanisms such as CORINAIR. The European Civil Aviation Conference (ECAC) has established a sub-group on Emission Calculation (EMCAL) within its ANCAT group. This sub-group produced a harmonised methodology for national air traffic emission inventories. A second sub-group (ERLIG-Emission Related Landing Charges Investigation Group) has been set up to create a single methodology for classifying aircraft according to their NO_x emissions for the potential purpose of emission charges, in which the aviation industry has expressed an interest.

ARTEMIS involved the application of the knowledge gained through projects and groups such as those mentioned above, and the closure of some of the major gaps in existing emission databases (primarily MEET and TRENDS), with particular emphasis on the following:

(i) *The allocation of emissions.* Current international reporting mechanisms only require domestic and ground-related emissions (*i.e.* emissions below 3000 feet). Emissions from international flights above 3000 feet are not allocated. International political pressure to allocate these emissions nationally is increasing, and the allocation procedure will have a large influence on the general methodology for emission calculation. In ARTEMIS, information on relevant allocation approaches was collected, and a state-of-the-art summary was compiled (Kalivoda and Kudrna, 2000).

(ii) *Aircraft/engine combinations not covered in the existing database*. Examples of these included turboprops and former Soviet aircraft, and measurements were conducted in order to fill the gaps in the emission data.

(iii) *In-flight emissions*. A great deal of in-flight emission data has been (and is still being) collected within projects such as POLINAT, AEROTRACE and AEROCERT, and extensive knowledge on emissions under cruise conditions has been gathered. However, these results are not included in most of the commonly-used emission inventory tools; access to measurements and databases for in-flight emissions arising from the EC aeronautical research projects has proven to be difficult and slow. In ARTEMIS, simulated in-flight measurements were conducted at Wroclaw Airport in Poland. The measurement campaign covered two different types of aircraft, and different conditions of engine age, power setting and temperature.

(iv) *Ground operations, such as additional emissions from engines during start-u*p. Emissions during engine start are not included in the Landing/Take-Off (LTO) Cycle, but will have a significant influence on total emissions of some pollutants from air transport, as well as on local air quality in the vicinity of airports. Within ARTEMIS, a common methodology was established for the measurement of NO_x, NO_2, N_2O, CO, HC, CH_4, SO_2 and PM_{10} emissions from

[62] http://reports.eea.europa.eu/EMEPCORINAIR4/en/page002.html
[63] ANCAT = Abatement of Nuisances caused by Air Transport

aircraft on the ground. This work benefited from IFU's experience in air traffic emission measurements, and from its involvement in other European projects such as AEROCERT and AEROJET, which also dealt with the improvement of measurement techniques. The work involved the non-intrusive scanning of numerous aircraft exhaust plumes, rather than conducting single 'spot' measurements. Finally, the data were used to create a set of emission factors for additional start-up emissions, as well as to support the creation of in-flight emission factors.

(v) *The influence of engine maintenance and ageing on emissions.* Engines are subject to normal performance degradation, which is regularly assessed. When engine performance drops to a pre-determined point, the engines are overhauled, this brings their performance back into standard specification.

(vi) *Auxiliary power units (APUs)*. An APU is a relatively small self-contained generator used in aircraft to start the main engines, usually with compressed air, and to provide electrical power and air conditioning while the aircraft is on the ground. In many aircraft, the APU can also provide electrical power in the air. An emission model was created for APU emissions. The increasing use of electronic equipment on aircraft, such as in-flight entertainment systems, has resulted in increased demands on APUs. The ARTEMIS work extended the assessment of APUs undertaken within the TRENDS methodology.

F2 Allocation of emissions

F2.1 Background

Current international reporting mechanisms only require domestic and ground-related emissions below 3000 feet. According to international protocols, emissions arising from aircraft operation above 3000 feet are not allocated to the Member States, but are treated as 'international' emissions, and therefore no national government is held responsible for them. International pressure to allocate these emissions nationally is increasing. A number of institutions, including the International Civil Aviation Organisation (ICAO) and UNFCCC, consider that changes are required in the emission allocation rules for international air traffic.

Several ways of allocating emissions are currently available, although not all of the options can be easily implemented using existing emission inventory tools. Some basic models allocate 50% to the departure airport and 50% to the destination airport, to countries flown over, or 100% of emissions to the country in which the aircraft is registered. Some of the proposed allocation methods require rather sophisticated modelling tools, as well as very detailed activity data.

The aim of this part of the ARTEMIS work was to collect information and relevant models, and deliver a state-of-the-art review of the international discussion in this area.

F2.2 The Kyoto Protocol

Based on the decisions made in the third session of the Conference of the Parties (according to the Kyoto Protocol), there are several possible approaches for allocating the emissions originating from international bunker fuels. The options are:

Option 1: No allocation.

Option 2: Allocation of global emissions from bunker fuels to Parties in proportion to their national emissions.

Option 3: Allocation to Parties according to the country where the bunker fuels are sold.

Option 4: Allocation to Parties according to the nationality of the transporting company, the company where the aircraft is registered, or the country of the operator.

Option 5: Allocation to Parties according to the country of departure or destination of an aircraft or a vessel. Alternatively the emissions related to the journey of an aircraft or vessel could be shared between the country of departure and the country of arrival.

Option 6: Allocation to Parties according to the country of departure or destination of passenger or cargo. Alternatively, the emissions related to the journey of a passenger or cargo could be shared by the country of departure and the country of arrival.

Option 7: Allocation to Parties according to the country of origin of the passenger or owner of the cargo.

Option 8: Allocation to the Party of emissions generated in it's national space.

F2.3 Emission charges at airports

Emission charges of airports, which have been in use since 1998, only take into account the landing and take-off cycle. An international charging system should also include the flight stages above 3000 feet. It is obvious that the formal or political effects are more important than 'proven' economic or environmental effects in both departure and arrival countries. In any case, the steady increase of traffic is more significant than a possible effect of the charges. The reporting bodies also agree that the introduction of an emission charge at many airports would be more efficient for world-wide emission reductions than higher charging levels at a few locations.

F2.4 Conclusions

Clearly, the different allocation options listed in the Kyoto Protocol require different methodologies and different data structures for the estimation of emission from civil aviation. **Table F-1** shows a summary of allocation methodologies. A methodology is termed 'two-dimensional' (2D) if it is based on aggregated emission data from representative flight profiles.

Option 1 can be neglected with regards to methodological needs, since no allocation of emissions from international aviation is done. This is the current situation. A simple two-dimensional methodology satisfies the needs of Options 2 to 7 (**Table F-2**). The UNECE methodology and the AvioMEET inventory tool are 2-dimensional. Both of these approaches use tables for each aircraft/engine combination, with total numbers for fuel consumption and emissions for a flight from airport 'A' to airport 'B' (a 'city pair'), and each number is only a function of the distance (between the cities) and the cruise altitude. Distance and altitude are therefore the only inputs for the calculation of emissions from a specific aircraft.

Table F-1: Summary of allocation methodologies.

	Option of allocation according to Kyoto Protocol	Requirements for inventory
Option 1:	No allocation.	no methodology needed
Option 2:	Allocation of global emissions from bunker fuels to Parties in proportion to their national emissions.	2D methodology
Option 3:	Allocation to Parties according to the country where the bunker fuels are sold.	2D methodology
Option 4:	Allocation to Parties according to the nationality of the transporting company, the company where the aircraft is registered, or the country of the operator.	2D methodology
Option 5:	Allocation to Parties according to the country of departure or destination of an aircraft or a vessel. Alternatively the emissions related to the journey of an aircraft or vessel could be shared between the country of departure and the country of arrival.	2D methodology
Option 6:	Allocation to Parties according to the country of departure or destination of passenger or cargo. Alternatively, the emissions related to the journey of a passenger or cargo could be shared by the country of departure and the country of arrival.	2D methodology
Option 7:	Allocation to Parties according to the country of origin of the passenger or owner of the cargo.	2D methodology
Option 8:	Allocation to the Party of emissions generated in it's national space.	3D methodology

As soon as emissions are allocated to the (national) space where they are generated, the 2D approach is not sufficient, so totals for the whole flight do not serve the needs of Option 8 at all. There is a large difference in the emission per kilometre if the aircraft is taking off, climbing, cruising or descending. Depending on the location of the departure airport within a country, and on the location of the destination, for one a given journey distance and cruise altitude a different emission will be allocated to the country.

This can be illustrated by the example of Vienna airport, which is situated in the east of Austria. On a flight of 1,000 km to the east, the aircraft will leave the Austrian territory after about 30 km, and will still be climbing. On the other hand, on a 1,000 km journey to the west, the aircraft will fly for 500 to 600 km until it leaves the Austrian territory, and with a much larger emissions being allocated to Austria.

To compute and allocate emissions appropriately, a three-dimensional methodology is necessary, whereby the actual emission at a distance x from the departure airport for a given aircraft/engine combination (with a specific distance and cruise altitude) are included. Data from the 3D model can be converted to 2D data easily by integrating the emissions over the whole distance of the mission. Unfortunately, it does not work the other way around.

The UNECE methodology and the AvioMEET inventory tool cannot be used to estimate emissions properly according to Kyoto Option 8, with only the MEET methodology suitable for this purpose (Kalivoda and Kudrna, 2000).

Table F-2: Summary of allocation methodologies.

	Pollutants included	LTO included	Total flight included	Option according to Kyoto Protocol	Input	Comment	Rate proposed
Emission calculation methodology used within the levy model							
Emission charges Zurich	HC NO_x	Yes	No	5 – dep./arr. country of vessel 6 – dep./arr. country of pass./cargo 8 – country of emis. generated*	Landing fee calculation model	Already used	Yes
Emission charges Sweden	HC NO_x	Yes	No	8 – country of emis. generated*	Landing fee calculation model	Already used	Yes
Emission charges Heathrow	NO_x	Yes	No	5 – dep./arr. country of vessel 6 – dep./arr. country of pass./cargo	Landing fee calculation model	Already used	Yes
Levy	CO_2, NO_x, contrails	Take off & landing	Yes	4 – nationality of comp./operat.	Fuel used Emission index database		Yes
Kerosene taxation	Kerosene	No	No	2 – general alloc. a/t nat. emis. 3 – country where fuel sold	Specific fuel consumption		Yes
Environmental charges	-	-	-	4 – nationality of comp./operat. 5 – dep./arr. country of vessel 6 – dep./arr. country of pass./cargo	-	General proposal	No
Emission trading	-	-	-	2 – general alloc. a/t nat. emis. 8 – country of emis. generated	-	General proposal	No
Tax on air pollution	NO_x	Yes	Yes	5 – dep./arr. country of vessel	Aircraft type		Yes
Allocation of aviation CO_2 emissions	CO_2	-	-	2 – general alloc. a/t nat. emis. 3 – country where fuel sold 4 – nationality of comp./operat. 5 – dep./arr. country of vessel 6 – dep./arr. country of pass./cargo 7 – origin country of pass./cargo 8 – country of emis. generated	-	General proposal	Yes
Inventory tool/methodology							
UNECE/ TFEI methodology	NO_x, HC, CO	Yes	Yes	2 – 7 (2D-methodology)	Generic aircraft, distance class of mission		No
Avio-MEET inventory tool	NO_x, HC, CO, H_2O, SO_2, CO_2	Yes	Yes	2 – 7 (2D-methodology)	Generic aircraft, distance of mission, optional: flight altitude and taxiing time		No
MEET methodology	NO_x, HC, CO, H_2O, SO_2, CO_2	Yes	Yes	2 – 7 (2D-methodology) AND 8 (3D-methodology)	Generic aircraft, distance of mission, optional: flight altitude and taxiing time		No
ANCAT/ EMCAL	NO_x, HC CO	Yes	Yes	2 – 7 (2D-methodology)	Generic aircraft, distance class of mission		No

(* can be used for Option 8 only for Zurich or Sweden)

F3 Measurement programme

F3.1 Overview

In addition to the allocation of emissions, the aspects of aircraft emissions covered in ARTEMIS were:

- Emissions from aircraft/engine combinations not covered in existing databases.
- In-flight emissions.
- Emissions during ground operations.
- The influence of engine maintenance and ageing on emissions.
- Emissions from auxiliary power units (APUs).

In line with the ARTEMIS objectives, a representative number of in-service aircraft engines of different engine types had to be measured. The challenge was to obtain information about aircraft engine emissions during all aircraft activities at airports. The emissions from main engines as well as APUs had to be investigated during typical operating conditions. Consequently, emissions during engine start-up, idle and similar conditions during taxiing, acceleration of aircraft on the taxiways and take-off all had to be measured. Where possible, the power settings of the ICAO LTO cycle had to be investigated (7%, 30%, 85%, 100 % of maximum thrust or power setting).

Various measurement campaigns were conducted at a number of airports. The measurements conducted at a given location provided information on more than one aspect of aircraft emissions. The following types of experiment were conducted:

(i) Measurements on main engines and APUs during ground operations (non-intrusive measurements.
(ii) Investigations of engine ageing and maintenance (intrusive measurements).
(iii) Measurements on former Soviet aircraft.

F3.2 Emissions from main engines and APUs during ground operations

Non-intrusive measurements

Non-intrusive exhaust measurements were performed on aircraft and APUs at Frankfurt/Main and Vienna-Scwechat airports using two Fourier Transform Infrared Spectrometry (FTIR) instruments and one Differential Optical Absorption Spectroscopy (DOAS) instrument.

Using FTIR, several compounds - including CO, CO_2, NO, NO_2, CH_4, H_2O - can be determined simultaneously with a single instrument. One of the FTIR instruments was operated in ‘passive mode’. In the passive measurement mode (FTIR emission spectrometry) the infrared radiation from hot exhaust gases is detected. The hot molecules emit infrared radiation at specific wavelengths and show characteristic signatures at the same infrared wavelengths, as in the case of absorption. The field of view of the spectrometer telescope has to be oriented as close as possible to the exhaust plume behind the turbine nozzle exit (up to a maximum distance of 50 m) and perpendicular to the exhaust plume. In this measurement configuration the depth of the exhaust plume corresponds to the inner diameter of the nozzle exit, excluding the by-pass. The ARTEMIS programme employed an improved version of the passive FTIR emission spectrometry for the measurement of aircraft engine emission indices (Heland and Schäfer, 1997, 1998; Schäfer *et al.*, 2000). The detection limits were: CO_2 0.1 %, CO 5 ppm and NO 8 ppm (given an exhaust diameter of 60 cm, and a measurement distance of approximately 30 m). NO_2, with a detection limit of 60 ppm, is not normally sensitive enough for routine measurements. With the measurement CO_2 concentrations at both the nozzle exit (by passive FTIR spectrometry) and directly behind the aircraft (by FTIR absorption spectrometry), and assuming the total combustion of the kerosene fuel, the emission indices for all other measured compounds could be determined.

To determine exhaust emissions of NO_2 and HC, further non-intrusive measurement methods (FTIR absorption spectrometry and DOAS) were used. These instruments are based on the physical effect that many trace gases absorb the radiation in the UV, visible and infrared spectral ranges. The radiation for FTIR is generated by an infrared source, and for DOAS by a xenon lamp for the UV/visible spectral range. This radiation is absorbed by the molecules in the exhaust plume on the way to the detector. The radiative transfer is described by the Beer-Lambert law. The inversion of incoming radiation produces path-integrated concentrations of exhaust compounds. Open paths of 80 to 150 m in length were installed in parallel directly behind the aircraft so that the exhaust gases were blown into the beam paths. The gas concentrations from the open-path FTIR absorption measurements were determined by the differential absorption method and least squares fitting of measured and simulated or reference transmittances. DOAS works with a grating spectrometer and filters to detect certain spectral ranges. Spectra analysis is based on fitting algorithms to reference absorption cross sections for the compounds to be determined. NO, NO_2, SO_2, O_3, benzene, toluene and xylene were measured with detection limits of about 1 ppb to 5 ppb. Thus the use of DOAS allows the measurement of NO_2 in aircraft exhaust.

Before starting the aircraft engine exhaust investigations a measurement campaign was performed with a kerosene-powered burner to compare and calibrate the different measurement methods which were used during aircraft exhaust gas measurements at airports. The burner was operated in that way that the different methods were applied for the exhaust gas investigations during the same time and at nearly the same exhaust gas volume. The burner, shown in **Figure F-1,** was built by the IFU. The power of the burner was around 150 kW. Fresh air was pumped into the burner tube by a fan. The temperature of the exhaust inside the tube was about 270 °C. For FTIR the detection limits for the various pollutants were as follows: CO_2 100 ppb, N_2O 20 ppb, CO 5 ppb, CH_4 30 ppb, NO 30 pbb, SO_2 200 ppb, NO_2 30 ppb, ethene 5 ppb, HCHO 10 ppb, and qualitative information of the unburnt hydrocarbon (UHC) content. For DOAS, the detection limits were: NO_2 5 ppb, SO_2 15 ppb, NO 5 ppb, benzene, toluene and xylene 5 ppb.

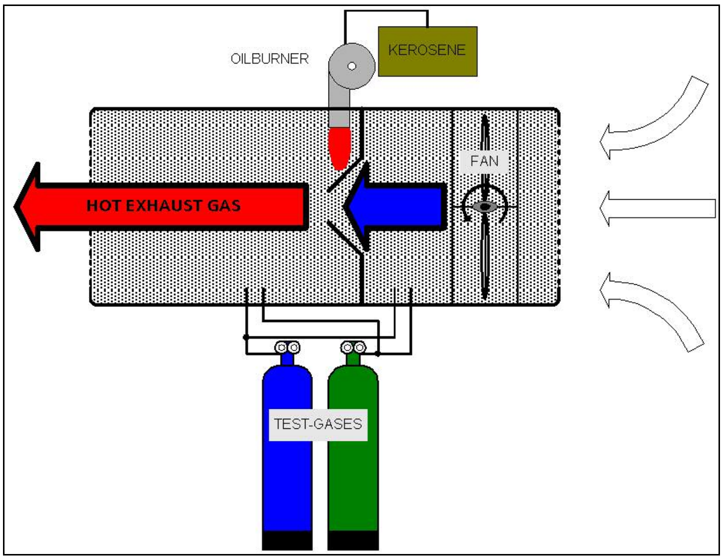


Figure F-1: Burner powered by kerosene for inter-comparison of the different measurement systems.

The application of the non-intrusive measurement methods is illustrated in **Figure F-2** (Schaefer *et al,* 2003). The passive FTIR spectrometer was installed in a van, whereas the FTIR absorption spectrometry and DOAS instruments were simultaneously operated on open paths directly behind the aircraft. In total, 33 aircraft engines and 47 APUs were investigated at ground level using passive FTIR spectrometry. A large number of aircraft (>130) were measured at Vienna-Scwechat airport using FTIR absorption spectrometry and DOAS, with an additional three aircraft being measured and Frankfurt/Main (Kalivoda and Bukovnik, 2005).

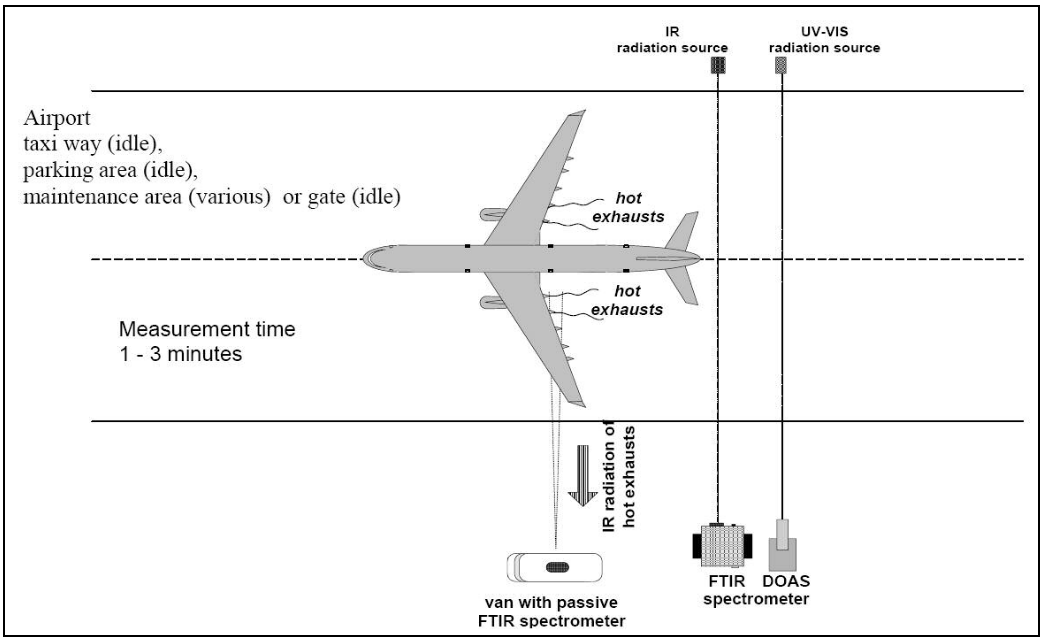


Figure F-2: Measurement configuration for passive remote sensing of aircraft exhausts by FTIR emission spectrometry at airports.

The quality of the FTIR emission spectrometry results for CO_2, CO, and NO - compared with values obtained using certified intrusive systems during engine runs on a test rig - was investigated as part of the projects AEROJET (Schäfer *et al*., 2000) and AEROJET2. The differences were almost all below 30%. Comparisons between measured CO emission indices and ICAO data for three engines[64] also showed deviations of less than 30%. The open-path measurement methods are accurate to within 5-10% (Haus *et al*., 1994). The aircraft engines and APUs listed in **Table F-3** were investigated at ground level using passive FTIR. Additional APU measurements were conducted using passive FTIR, and are summarised in **Table F-4** for the summer and winter campaigns.

Table F-3: Engines and APUs measured by passive FTIR spectrometry.

Engine Type	Nozzle diameter	Usage	Engine Type	Nozzle diameter	Usage
CFM56-3B1	115 cm	Civil, med. range	PW123B	43 cm	Civil, short range
CFM56-3B2	115 cm	Civil, med. range	PW150A	45 cm	Civil, short range
CFM56-3C1	115 cm	Civil, med. range	RB211-524D4	90 cm	Civil, long range
CFM56-5A1	65 cm	Civil, med. range	RB211-524D4X	90 cm	Civil, long range
CFM56-5B1	66 cm	Civil, med. range	RB211-524H2	170 cm	Civil, long range
CFM56-5B3/P	66 cm	Civil, med. range	RB211-524H-36	170 cm	Civil, long range
CFM56-5B4/2	66 cm	Civil, med. range	RB211-535C	84 cm	Civil, med. range
CFM56-5B4/2P	66 cm	Civil, med. range	RB211-535C-37	84 cm	Civil, med. range
CFM56-5C2	140 cm	Civil, long range	RB211-535E4	145 cm	Civil, med. range
CFM56-7B22/2	68 cm	Civil, med. range	RB211-535E4-37	145 cm	Civil, med. range
CFM56-7B26	68 cm	Civil, med. range	RR M45H	50 cm	Civil bus. Jets
CFM56-7B27	68 cm	Civil, med. range	TAY MK 620	90 cm	Civil, short range
GE CF 34-3A	43 cm	Civil, short range	V2500-A1	124 cm	Civil, med. range
GE CF 34-3A1	43 cm	Civil, short range	APS2000	35 cm	APU
GE CF 34-3B1	43 cm	Civil, short range	APS3200	35 cm	APU
GE CF6-50E2	60 cm	Civil, long range	GT CP85-98DHF	35 cm	APU
GE CF 700-2D2	44 cm	Civil bus. Jets	GT CP331-200/250	55 cm	APU
GE90-85B	150 cm	Civil, long range	GT CP331-500	55 cm	APU
JT8D-15	108 cm	Civil, med. range	GT CP660-4	55 cm	APU
JT8D-217C	95 cm	Civil, med. range	PW901A	55 cm	APU

Table F-4: APUs measured using passive FTIR spectrometry.

Summer campaign				Winter campaign			
Aircraft registration	Aircraft type	Airline	APU type	Aircraft registration	Aircraft type	Airline	APU type
PH-BTF	B737-406	KLM	APS2000	D-AIPT	A320-200	Deutsche Lufthansa	APS3200
G-BDXO	B747-236	BA	GTCP660-4	PH-BTF	B737-406	KLM	APS2000
G-BNLP	B747-436	BA	PW901A	D-AHFB	B737-800	Hapag Lloyd	GTCP85-98DHF
G-CIVV	B747-436	BA	PW901A	G-BDXO	B747-236	BA	GTCP660-4
G-BNLK	B747-436	BA	PW901A	D-ABTH	B747-400	Deutsche Lufthansa	PW901A
G-CIVL	B747-436	BA	PW901A	D-ABTD	B747-400	Deutsche Lufthansa	PW901A
G-BIKY	B757-236	BA	GTCP331-200/250	D-ABVU	B747-400	Deutsche Lufthansa	PW901A
G-BMRA	B757-236	BA	GTCP331-200/250	G-BNLT	B747-436	BA	PW901A
G-BIKZ	B757-236	BA	GTCP331-200/250	G-BYGA	B747-436	BA	PW901A
G-ZZZD	B777-236	BA	GTCP331-500	G-CIVN	B747-436	BA	PW901A
G-CIVE	B747-436	BA	PW901A	G-BNLV	B747-436	BA	PW901A
G-BNLE	B747-436	BA	PW901A	G-BNLP	B747-436	BA	PW901A
G-BNLM	B747-436	BA	PW901A	G-CIVV	B747-436	BA	PW901A
G-BNLI	B747-436	BA	PW901A	G-BNLK	B747-436	BA	PW901A
G-BNLP	B747-436	BA	PW901A	G-CIVL	B747-436	BA	PW901A
G-BYGE	B747-436	BA	PW901A	G-BIKY	B757-236	BA	GTCP331-200/250
G-CIVO	B747-436	BA	PW901A	G-BMRA	B757-236	BA	GTCP331-200/250
G-BNWU	B767-336	BA		G-BIKZ	B757-236	BA	GTCP331-200/250
G-YMMK	B777-236	BA	GTCP331-500	G-VIIJ	B777-236	BA	GTCP331-500
				G-VIIM	B777-236	BA	GTCP331-500
				G-ZZZD	B777-236	BA	GTCP331-500

[64] Obtained during run-up tests of engines measured as part of AEROJET2 at London Heathrow.

Information on the interaction between the exhaust plume of an aircraft jet engine and ambient air is required for the application of small-scale chemistry-transport models to investigate airport air quality. This interaction is not well understood. In order to study the interaction, spatial information about the plume is required, and FTIR emission spectroscopy may be applied to characterise plumes spatially. A scanning imaging FTIR system (SIGIS) was operated during the winter campaign. This comprised an interferometer (Bruker OPAG), an azimuth-elevation-scanning mirror, a data acquisition and control system with digital signal processors (DSP), an infrared camera and a personal computer.

VOC measurements

Samples of ambient air were taken in stainless steel canisters during the winter campaign and analysed with a GC (Varian 3600CX) in the laboratory. One calibration canister containing benzene and *n*-butane in nitrogen, and one canister containing 70 NMHC compounds in nitrogen were used for identification purposes. The hydrocarbons of the sample were detected by a flame ionisation detector (FID), held at 250°C. The precision of this system was less than 0.9% for compounds in the range between 5 to 50 ppbv. For aromatic compounds the precision for the same concentration range was 1% for benzene and toluene, 2% for ethylbenzene and 3% for the xylenes. The detection limit was between 10 and 15 pptv for most compounds.

F3.3 Effects of engine ageing and maintenance

In a second step, measurements were performed on the most commonly used engines in Europe, and under different ambient conditions (summer/winter, dry/wet weather), for different engine age and maintenance levels (new/old engine, engine before/after overhaul), and for engine start-up as well as for the different power settings of the LTO cycle. Prior to ARTEMIS, data from such measurements were not widely available (Kalivoda and Bukovnik, 2005). The main engines measured during the Frankfurt-Main and Vienna-Schwechat campaigns are listed in **Table F-5** and **Table F-6** respectively.

State-of-the-art measurement methods for aircraft engine exhaust emissions are *in situ* techniques for engine certification (CO_2, NO, NO_2, HC concentrations and smoke number), which are recommended by regulations of the International Civil Aviation Organisation (ICAO, 1993). The measurements involve probe sampling, which requires a multi-aperture sampling rake to be placed in the engine exhausts. The exhaust gas is sampled from a number of locations behind the engine. From this rake the gas is passed to analytical instruments via a single transfer line. Care must be taken to quench the sample to avoid chemical reactions in the transfer line, the temperature of which is maintained at 150 ±5 ^{o}C to avoid condensation of water and volatile hydrocarbons. In some cases the sampling rake, which is usually cruciform, is rotated to allow for asymmetry in the distribution of emissions. At the end of the transfer line the sample is analysed for CO_2 and CO using non-dispersive infrared absorption (NDIR), for HC using a heated flame ionisation detector (FID), and for NO_x using a chemiluminescence analyser. Each instrument is calibrated using a calibration gas traceable to national or international standards. A known volume of sampled gas is passed through a filter paper to extract particles. The Society of Automotive Engineers smoke number is determined from the reflectance of a stained filter paper (SAE, 1990). Current legislation by SAE standard (SAE, 1982) requires demonstration that the probe collects a representative sample and includes correction for interference effects. The data collection time for all species (effectively determined by the smoke measurement) at one point is about five minutes per engine condition. The probe is fitted with sensors for pressure (total and static) and temperature.

Table F-5: Main engines measured during the Frankfurt-Main campaign.

Aircraft registration	Aircraft type	Airline	Engine type
D-ABEO	B737-300	Deutsche Lufthansa	CFM56-3C1
D-AHFB	B737-800	Hapag Lloyd	CFM56-7B26
D-ABYR	B747-200	Deutsche Lufthansa	GE CF6-50E2

Table F-6: Main engines measured during the Vienna-Schwechat campaign.

Aircraft registration	Aircraft type	Airline	Engine type	Aircraft registration	Aircraft type	Airline	Engine type
OE-LBN	A-320-214	AUA	CFM56-5B4/2	OE-LFQ	70	AUA	RR-Tay MK 620
OE-LCG	CRJ 200LR	Tyrolean Airways	GE CF 34-3B2	OE-LCI	CRJ 200LR	Tyrolean Airways	GE CF 34-3B4
OE-LRG	CRJ 100LR	Lauda Air	GE CF 34-3A	OE-LBB	A321-111	AUA	CFM56-5B1
OE-LBC	A321-111	AUA	CFM56-5B1	OE-LFK	70	Tyrolean Airways	RR-Tay MK 620
OE-LFH	70	Tyrolean Airways	RR-Tay MK 620	OE-LMN	MD-87	AUA	JT8D-217C
OE-LBP	A320-214	AUA	CFM56-5B4/2P	OE-LTJ	300Q	Tyrolean Airways	PW 123B
OE-LBR	A320-214	AUA	CFM56-5B4/2	OE-LCF	CRJ 200LR	Tyrolean Airways	GE CF 34-3B1
OE-LGA	DHC8-402	Tyrolean Airways	PW 150A	OE-LBC	A320-111	AUA	CFM56-5B1
OE-LTO	DHC8-314	Tyrolean Airways	DHC-8-300Q	OE-LBO	A320-214	AUA	CFM56-5B4/2P
OE-LMN	MD-87	AUA	JT8D-217C	OE-LFR	70	AUA	RR-Tay MK 620
OE-LTH	300Q	Tyrolean Airways	PW 123B	OE-LBA	A321-111	AUA	CFM56-5B1
OE-LTG	300Q	Tyrolean Airways	PW 123B	OE-LGC	400Q	Tyrolean Airways	PW 150A
OE-LTM	300Q	Tyrolean Airways	PW 123B	OE-LFO	70	Tyrolean Airways	RR-Tay MK 620
OE-LTL	300Q	Tyrolean Airways	PW 123B	OE-LTM	300Q	Tyrolean Airways	PW 123B
OE-LFG	70	Tyrolean Airways	RR-Tay MK 620	OE-LCG	CRJ 200LR	Tyrolean Airways	GE CF 34-3B2
OE-LBN	A320-214	AUA	CFM56-5B4/2P	OE-LMO	MD-87	AUA	JT8D-217C
OE-LGD	400Q	Tyrolean Airways	PW 150A	OE-LRF	CRJ 100LR	LAUDA AIR	GE CF 34-3A1
OE-LGE	400Q	Tyrolean Airways	PW 150A	OE-LTH	300Q	Tyrolean Airways	PW 123B
OE-LBQ	A320-214	AUA	CFM56-5B4/2P	OE-LBF	A321-211	AUA	CFM56-5B3/P
OE-LFO	70	Tyrolean Airways	RR-Tay MK 620	OE-LGA	400Q	Tyrolean Airways	PW 150A o
OE-LFR	70	AUA	RR-Tay MK 620	OE-LTG	300Q	Tyrolean Airways	PW 123B
OE-LGA	DHC8-402	Tyrolean Airways		OE-LBU	A320-214	AUA	CFM56-5B4/2P
OE-LFI	70	Tyrolean Airways	RR-Tay MK 620	OE-LFK	70	Tyrolean Airways	RR-Tay MK 620
OE-LBA	A321-111	AUA	CFM56-5B1	OE-LBT	A320-214	AUA	CFM56-5B4/2P
OE-LCM	CRJ 200LR	Tyrolean Airways	GE CF 34-3B6	OE-LTP	300Q	Tyrolean Airways	PW 123B
OE-LMO	MD-87	AUA	JT8D-217C	OE-LTI	300Q	Tyrolean Airways	PW 123B
OE-LTG	300Q	Tyrolean Airways	PW 123B	OE-LFT	70	AUA	RR-Tay MK 620
OE-LBP	A320-214	AUA	CFM56-5B4/2P	OE-LNK	B737 800	LAUDA AIR	CFM 56-7B27
OE-LBC	A320-111	AUA	CFM56-5B1	OE-LGA	400Q	Tyrolean Airways	PW 150A
OE-LGB	DHC8-402	Tyrolean Airways		OE-LFG	70	Tyrolean Airways	RR-Tay MK 620
OE-LCG	CRJ 200LR	Tyrolean Airways	GE CF 34-3B2	OE-LGB	400Q	Tyrolean Airways	PW 150A
OE-LBO	A320-214	AUA	CFM56-5B4/2P	OE-LTG	300Q	Tyrolean Airways	PW 123B
OE-LBB	A321-111	AUA	CFM56-5B1	OE-LTJ	300Q	Tyrolean Airways	PW 123B
OE-LCF	CRJ 200LR	Tyrolean Airways	GE CF 34-3B1	OE-LBB	A321-111	AUA	CFM56-5B1
OE-LFG	70	Tyrolean Airways	RR-Tay MK 620	OE-LTM	300Q	Tyrolean Airways	PW 123B
OE-LBT	A320-214	AUA	CFM56-5B4/2P	OE-LFI	70	Tyrolean Airways	RR-Tay MK 620
OE-LRF	CRJ 100LR	LAUDA AIR	GE CF 34-3A1	OE-LFQ	70	AUA	RR-Tay MK 620
OE-LTH	300Q	Tyrolean Airways	PW 123B	OE-LNL	B737 600	LAUDA AIR	CFM 56-7B22/2
OE-LGD	400Q	Tyrolean Airways	PW 150A	OE-LFO	70	Tyrolean Airways	RR-Tay MK 620
OE-LTM	300Q	Tyrolean Airways	PW 123B	OE-LBS	A320-214	AUA	CFM56-5B4/2P
OE-LCO	CRJ 200LR	Tyrolean Airways	GE CF 34-3B8	OE-LFK	70	Tyrolean Airways	RR-Tay MK 620
OE-LMN	MD-87	AUA	JT8D-217C	OE-LCP	CRJ 200LR	Tyrolean Airways	GE CF 34-3B9
OE-LMN	MD-87	AUA	JT8D-217C	OE-LBF	A321-211	AUA	CFM56-5B3/P no
OE-LBN	A320-214	AUA	CFM56-5B4/2P	OE-LCH	CRJ 200LR	Tyrolean Airways	GE CF 34-3B3
OE-LTH	300Q	Tyrolean Airways	PW 123B	OE-LFR	70	AUA	RR-Tay MK 620
OE-LBE	A321-211	AUA	CFM56-5B3/P	OE-LMO	MD-87	AUA	JT8D-217C
OE-LFT	70	AUA	RR-Tay MK 620	OE-LBC	A320-111	AUA	CFM56-5B1
OE-LAH	A340-211	AUA	CFM56-5C2	OE-LCM	CRJ 200LR	Tyrolean Airways	GE CF 34-3B6
OE-LBA	A321-111	AUA	CFM56-5B1	OE-LRE	CRJ 100LR	LAUDA AIR	GE CF 34-3A1
OE-LFL	70	Tyrolean Airways	RR-Tay MK 620	OE-LFL	70	Tyrolean Airways	RR-Tay MK 620
OE-LFR	70	AUA	RR-Tay MK 620	OE-LFH	70	Tyrolean Airways	RR-Tay MK 620
OE-LCH	CRJ 200LR	Tyrolean Airways	GE CF 34-3B3	OE-LTP	300Q	Tyrolean Airways	PW 123B
OE-LBO	A320-214	AUA	CFM56-5B4/2P	OE-LBT	A320-214	AUA	CFM56-5B4/2P
OE-LTL	300Q	Tyrolean Airways	PW 123B	OE-LBQ	A320-214	AUA	CFM56-5B4/2P
OE-LGD	400Q	Tyrolean Airways	PW 150A	OE-LBN	A320-214	AUA	CFM56-5B4/2P
OE-LBQ	A320-214	AUA	CFM56-5B4/2P	OE-LBU	A320-214	AUA	CFM56-5B4/2P
OE-LTD	DHC-8-300	Tyrolean Airways	PW 123B	OE-LTM	300Q	Tyrolean Airways	PW 123B
OE-LBN	A320-214	AUA	CFM56-5B4/2P	OE-LCF	CRJ 200LR	Tyrolean Airways	GE CF 34-3B1
OE-LNK	B737 800	LAUDA AIR	CFM 56-7B27	OE-LGA	400Q	Tyrolean Airways	PW 150A o
OE-LTM	300Q	Tyrolean Airways	PW 123B	OE-LGB	400Q	Tyrolean Airways	PW 150A
OE-LFI	70	Tyrolean Airways	RR-Tay MK 620	OE-LBR	A320-214	AUA	CFM56-5B4/2
OE-LTL	300Q	Tyrolean Airways	PW 123B	OE-LBO	A320-214	AUA	CFM56-5B4/2P
OE-LTG	300Q	Tyrolean Airways	PW 123B	OE-LCG	CRJ 200LR	Tyrolean Airways	GE CF 34-3B2
OE-LTH	300Q	Tyrolean Airways	PW 123B	OE-LBA	A321-111	AUA	CFM56-5B1
OE-LFP	70	AUA	RR-Tay MK 620	OE-LFG	70	Tyrolean Airways	RR-Tay MK 620
OE-LFT	70	AUA	RR-Tay MK 620	OE-LTG	300Q	Tyrolean Airways	PW 123B o
OE-LMO	MD-87	AUA	JT8D-217C	OE-LTH	300Q	Tyrolean Airways	PW 123B
OE-LCP	CRJ 200LR	Tyrolean Airways	GE CF 34-3B9	OE-LRF	CRJ 100LR	LAUDA AIR	GE CF 34-3A1
				OE-LCI	CRJ 200LR	Tyrolean Airways	GE CF 34-3B4

F3.4 Measurements on former Soviet aircraft

Simulated in-flight measurements on former Soviet aircraft were performed at Wroclaw-Strachowice airport, coordinated by Czyste Powietrze, using the set-up shown in **Figure F-3 (**Gostomczyk *et al,* 2003). Measurements were made on the combustion gas from the following aircraft:

- Aircraft TU154, with engine D-30KU during starting and heating, and with loads of 61%, 81% and 95%.
- Jet aircraft type Al-25 (aircraft JAK – 40) with engine loads of 52%, 80% and 100%.

Different conditions of engine age and temperature were measured also.

The pollutants measured included HC, O_2, CO_2, CO, NO and SO_2. The temperature and volume flow rate of the combustion gas were also recorded. An infra red particle sizer (IPS) system was used for the measurement of particles size. Particle number, surface area and volume of particles per cubic meter were also calculated. The measurements which were performed are summarised in **Table F-7**.

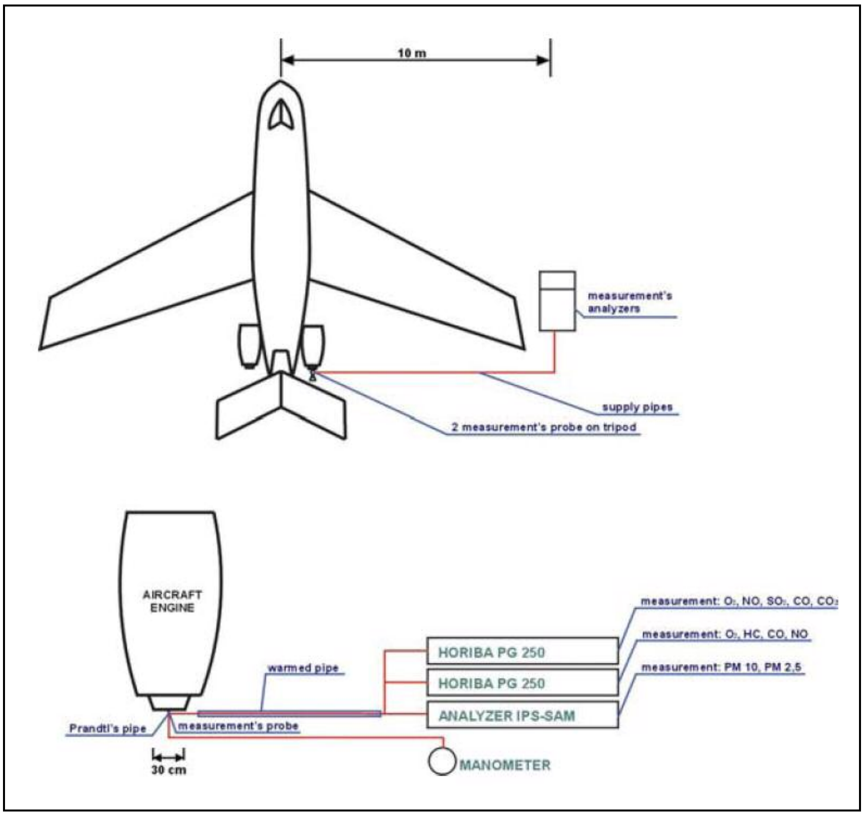


Figure F-3: Measurement set-up at Wroclaw-Strachowice airport (Gostomczyk *et al,* 2003).

Table F-7: Measurements conducted at Wroclaw-Strachowice airport.

	Campaign 1	Campaign 2	Campaign 3	Campaign 4	Campaign 5	Campaign 6	Campaign 7	Campaign 8
Date	03/08/01	04/09/01	21/10/01	07/11/01	31/01/02	31/01/02	12/09/02	12/09/02
Aircraft	TU-154M	TU-154M	JAK-40	JAL-40	TU-154M	TU-154M	TU-154M	TU-154M
Total hours	2,468	2,481	1,242	1,286	1,624	1,014		
Number of services	2	2	1	1				
Number of hours after service	468	481	442	468	813	813		
Atmospheric pressure (hPa)	998	1,007	1,004	1,004	1,009	1,009	1,006	1,006
Temperature (^oC)	25.1	20.7	10	9.8	10.1	10.1	21.6	21.6
Humidity (%)	63	67	78	74	64	64	63	63
Wind speed (m/s)	2	4	7	6	4	4	5	5
Cloud cover	7/8	7/8	7/8	7/8	7/8	7/8	7/8	7/8

F4 Results of measurement campaigns

F4.1 Main engines during ground operations

The emission factors measured during the summer and winter campaigns are shown in **Tables F-8** and **F-9** respectively. Most of the measurements were performed during summer (mean air temperature about 20°C). A few measurements (some B747-236, B747-436, and B777-236 aircraft) were conducted in March 1999, with temperatures around 11°C. The emission factors for the main engines different aircraft, measured using FTIR emission spectrometry, are given in **Table F-10**.

The data in **Table F-8** show that there was a high level of variance in emission factors during idle conditions for each type of aircraft. The measured NO_x emission factors were found to be lower than those given by the ICAO from certification measurements, potentially supporting the efforts made by manufacturers and airlines to reduce NO_x emissions from aircraft. A comparison between summer and winter conditions was only possible with two engines. Lower CO emissions were observed during winter.

Table F-8: Measured emission factors and mean fuel consumption for the main engines of different aircraft during the summer campaign (**‘**bdl’ = below detection limit; minimum and maximum values are given in brackets; ‘No.’ = number of measured aircraft). The corresponding ICAO data are also given.

Aircraft	No.	Engine type	N1 (%)	Fuel flow (kg/h)	CO (g/kg)	NO (g/kg)	NO_x (g/kg)
A320-231	1	V2500-A1	Idle	n/a	7.2 ± 4.59 (2.5 - 13.0) ICAO: 7.76	0.8 ± 1.02 (bdl - 2.5)	1.3 ± 1.56 (bdl - 3.8) ICAO: 5.91
B737-306	1	CFM56-3B1	Idle	n/a	37.6 ICAO: 34.40	0.7	1.0 ICAO: 3.90
B737-382	1	CFM56-3B2	Idle	n/a	27. Apr ICAO: 30.10	0.3	0.5 ICAO: 4.10
B737-406	1	CFM56-3B2	Idle	n/a	33.7 ± 1.09 (32.7 - 34.8) ICAO: 30.10	bdl	bdl ICAO: 4.10
B737-8K2	3	CFM56-7B27	Idle	n/a	20.3 ± 8.37 (8.9 - 34.5) ICAO: 17.90	0.3 ± 0.24 (bdl - 0.6)	0.4 ± 0.37 (bdl - 0.9) ICAO: 4.80
B747-236	1	RB211-524D4X	Idle	n/a	26.0 ± 4.35 (21.0 - 31.2) ICAO: 9.30	bdl	bdl ICAO: 4.41
B757-236	1	RB211-535C	Idle	n/a	11. Aug (11.7 - 12.0) ICAO: 18.79	0.5	0.7 ICAO: 3.44
B757-236	5	RB211-535C-37	Idle	639 ± 31 ICAO: 720	7.5 ± 2.10 (0.7 - 11.0) ICAO: 18.79	0.3 ± 0.17 (bdl - 0.6)	0.4 ± 0.27 (bdl - 0.9) ICAO: 3.44
B757-236	1	RB211-535E4	Idle	n/a	6.7 ± 0.12 (6.6 - 13.4) ICAO: 15.44	0.4 ± 0.07 (0.3 - 0.5)	0.6 ± 0.10 (0.5 - 0.7) ICAO: 4.30
B757-236	2	RB211-535E4-37	Idle	517 ± 22 ICAO: 684	9.2 ± 2.93 (5.5 - 13.4) ICAO: 15.44	bdl	bdl ICAO: 4.30
B777-236	2	GE90-85B	Idle	n/a	39.1 ± 24.62 (2.7 - 64.1) ICAO: 13.67	0.3 ± 0.27 (bdl - 0.5)	0.4 ± 0.42 (bdl - 0.8) ICAO: 5.69

Table F-9: Measured emission factors and mean fuel consumption for the main engines of different aircraft during the winter campaign (**'**bdl' = below detection limit; minimum and maximum values are given in brackets; 'No.' = number of measured aircraft). The corresponding ICAO data are also given.

Aircraft	No.	Engine type	N1 (%)	Fuel flow (kg/h)	CO (g/kg)	NO (g/kg)	NOx (g/kg)
A319-131	13	V2522-A5	Idle	n/a ICAO: 424.8	10.09 ± 5.29 (3.8 – 24.7) ICAO: 13.42	0.43 ± 0.86 (bdl – 1.0)	0.66 ± 1.32 (bdl – 1.5) ICAO:
A319-131	4	V2522-A5	21.6 ± 1.2	847 ± 290 ICAO: 424.8	16.97 ± 5.45 (5.0 – 20.8) ICAO: 13.42	0.49 ± 0.70 (bdl – 1.0)	0.76 ± 1.70 (bdl – 1.5) ICAO: 4.55
A320-231	1	V2500-A1	Idle	n/a ICAO: 446.4	41730 ICAO: 7.76	20121	33298 ICAO: 5.91
A320-232	8	V2527-A5	Idle	n/a ICAO: 460.8	16.97 ± 0.80 (6.4 – 18.3) ICAO: 12.43	0.33 ± 0.46 (bdl – 1.6)	0.50 ± 0.71 (bdl – 2.4) ICAO: 4.7
A320-232	1	V2527-A5	18.9	801 ICAO: 460.8	15.42 ICAO: 12.43	0.47	0.72 ICAO: 4.7
A321-231	1	V2533-A5	Idle	n/a ICAO: 490.7	26938 ICAO: 9.32	0.26	0.40 ICAO: 5.24
B777-236	1	GE90-85B	Idle	n/a ICAO: 1015.2	46784 ICAO: 13.67	bdl	bdl ICAO: 5.69
B777-436	1	RR Trent 895-17	Idle	n/a ICAO: 1188	22.53 ICAO: 14.71	bdl	bdl ICAO: 5.11
B777-236	1	RR Trent 895-17	Idle	n/a ICAO: 1188	38520 ICAO: 14.71	bdl	bdl ICAO: 5.11

Table F-10: Measured mean emission indices of main engines of different aircraft by FTIR emission spectrometry ('bdl' = below detection limit). The minimum and maximum values of all measured data are given in brackets. NO_x is stated in terms of NO_2 equivalents.

Aircraft	No	Engine type	N1 (%)	CO (g/kg)	NO (g/kg)	NO_x (g/kg)
A320-211	1	CFM56-5A1	Idle	15.5	bdl	bdl
A320-214	2	CFM56-5B4/2	Var	44.2 (30.5-62.3)	0.7 (0.5 - 1.5)	1.1 (0.8 - 2.2)
A320-214	7	CFM56-5B4/2P	Idle	50.5 (21.3-72.6)	0.6 (bdl - 0.8)	0.9 (bdl - 1.2)
A320-231	1	V2500-A1	Idle	7.2 (2.5 - 13.0)	0.8 (bdl - 2.5)	1.3 (bdl - 3.8)
A321-111	3	CFM56-5B1	Idle	49.9 (23.0-71.9)	0.6 (0.5 - 0.7)	0.9 (0.7 - 1.1)
A321-211	1	CFM56-5B3/P	Idle	55.7 (50.7-63.9)	0.5 (bdl - 0.7)	0.7 (bdl - 1.0)
A340-211	1	CFM56-5C2	Idle	6.0	bdl	bdl
B737-300	1	CFM56-3C1	Idle	29.8 (19.9-37.1)	1.4 (1.2 - 1.5)	2.1 (1.9 - 2.3)
B737-306	1	CFM56-3B1	Idle	37.6	0.7	1.0
B737-382	1	CFM56-3B2	Idle	27.4	0.3	0.5
B737-406	1	CFM56-3B2	Idle	33.7	bdl	bdl
B737-600	1	CFM56-7B22/2	Idle	59.6 (45.9-73.4)	0.9 (0.6 - 1.1)	1.4 (1.0 - 1.8)
B737-800	1	CFM56-7B26	Idle	17.6	1.2	1.9
B737-800	1	CFM56-7B27	Idle	25.7 (17.3-33.8)	0.7 (0.4 - 0.9)	1.0 (0.7 - 1.4)
B737-8K2	3	CFM56-7B27	Idle	20.3 (8.9 - 34.5)	0.3 (bdl - 0.6)	0.4 (bdl - 0.9)
B747-200	1	GE CF 6-50E2	Idle	32.6	1.5	2.3
B747-236	3	RB211-524D4	Var	29.7 (6.6 - 93.7)	2.1 (0.1 - 4.6)	3.2 (0.1 - 7.1)
B747-236	1	RB211-524D4X	Idle	26.0 (21.0-31.2)	bdl	bdl
B747-436	7	RB211-524H2	Var	7.8 (0.3 - 23.3)	2.3 (bdl-15.5)	3.5 (bdl-23.8)
B757-236	2	RB211-535C	Idle	11.8 (11.7-12.0)	0.5	0.7
B757-236	5	RB211-535C-37	Idle	7.5 (3.0 - 11.0)	0.3 (bdl - 0.6)	0.4 (bdl - 0.9)
B757-236	1	RB211-535E4	Idle	6.7 (6.6 - 13.4)	0.4 (0.3 - 0.5)	0.6 (0.5 - 0.7)
B757-236	2	RB211-535E4-37	Idle	9.2 (5.5 - 13.4)	bdl	bdl
B767-336	1	RB211-524H-36	Idle	7.3	1.3	1.9
B777-236	7	GE90-85B	Var	27.7 (2.2 - 64.1)	1.9 (0.5 - 6.7)	3.0 (0.8-10.3)
MD-87	1	JT8D-217C	Idle	10.3 (9.4 - 11.2)	bdl	bdl
Fokker 70	10	RR-Tay MK620	Idle	23.1 (11.5-46.7)	0.2 (bdl - 2.6)	0.3 (bdl - 4.0)
CRJ 100LR	1	GE CF 34-3A	Idle	39.2 (38.0-40.5)	0.7	1.0
CRJ 100LR	2	GE CF 34-3A1	Idle	36.7 (31.0-46.6)	0.6 (0.5 - 0.8)	1.0 (0.8 - 1.2)
CRJ 200LR	8	GE CF 34-3B	Idle	38.9 (10.2-57.3)	0.7 (0.5 - 0.9)	1.0 (0.8 - 1.4)
DHC-8-300Q	8	PW 123B	Idle	9.5 (2.2 - 27.0)	1.1 (bdl - 9.5)	1.7 (bdl-14.5)
DHC-8-400Q	5	PW 150A	Idle	8.3 (3.3 - 17.0)	0.6 (bdl - 1.4)	0.8 (bdl - 2.2)

Table F-11: Measured emission factors for main engines of different aircraft, and mean fuel flow with standard deviation. The minimum and maximum values of all measured data are given in bracket ('bdl' = below detection limit; 'No.' = number of measured aircraft; 'Var' = variable power setting; 'A' = approach (30 % N1); 'C' = cruise (85 % N1); 'TO' = take off (100 % N1). The corresponding ICAO data are given.

Aircraft	No.	Engine type	N1 (%)	Fuel flow (kg/h)	CO (g/kg)	NO (g/kg)	NOx (g/kg)
A320-211	1	CFM56-5A1	Idle	n/a	15.5 ICAO: 17.60	bdl	bdl ICAO: 4.0
A320-214	2	CFM56-5B4/2	Var	601 ± 291	44.2 ± 9.82 (30.5 - 62.3)	0.7 ± 0.29 (0.5 - 1.5)	1.1 ± 0.45 (0.8 - 2.2)
A320-214	1	CFM56-5B4/2	Idle	472.8 ICAO: 435.6	48.8 ± 7.78 (43.4 - 62.3) ICAO: 37.10	0.6 ± 0.07 (0.5 - 0.7)	0.9 ± 0.11 (0.8 - 1.1) ICAO: 4.49
A320-214	7	CFM56-5B4/2P	Idle	395 ± 15 ICAO: 432	50.5 ± 12.67 (21.3 - 72.6) ICAO: 40.10	0.6 ± 0.18 (bdl - 0.8)	0.9 ± 0.28 (bdl - 1.2) ICAO: 3.90
A320-231	1	V2500-A1	Idle	n/a	7.2 ± 4.59 (2.5 - 13.0) ICAO: 7.76	0.8 ± 1.02 (bdl - 2.5)	1.3 ± 1.56 (bdl - 3.8) ICAO: 5.91
A321-111	3	CFM56-5B1	Idle	428 ± 50 ICAO: 421.2	49.9 ± 12.40 (23.0 - 71.9) ICAO: 28.40	0.6 ± 0.18 (0.5 - 0.7)	0.9 ± 0.28 (0.7 - 1.1) ICAO: 4.60
A321-211	1	CFM56-5B3/P	Idle	380 ICAO: 414	55.7 ± 5.95 (50.7 - 63.9) ICAO: 19.20	0.5 ± 0.32 (bdl - 0.7)	0.7 ± 0.49 (bdl - 1.0) ICAO: 4.70
A340-211	1	CFM56-5C2	Idle	n/a	6.0 ICAO: 34.00	bdl	bdl ICAO: 4.19
B737-300	1	CFM56-3C1	Idle	n/a	29.8 ± 8.85 (19.9 - 37.1) ICAO: 26.80	1.4 □ 0.16 (1.2 - 1.5)	2.1 ± 0.24 (1.9 - 2.3) ICAO: 4.30
B737-306	1	CFM56-3B1	Idle	n/a	37.6 ICAO: 34.40	0.7	1.0 ICAO: 3.90
B737-382	1	CFM56-3B2	Idle	n/a	27.4 ICAO: 30.10	0.3	0.5 ICAO: 4.10
B737-406	1	CFM56-3B2	Idle	n/a	33.7 ± 1.09 (32.7 - 34.8) ICAO: 30.10	bdl	bdl ICAO: 4.10
B737-600	1	CFM56-7B22/2	Idle	n/a	59.6 ± 19.47 (45.9 - 73.4) ICAO: 45.35	0.9 ± 0.37 (0.6 - 1.1)	1.4 ± 0.56 (1.0 - 1.8) ICAO: 3.94
B737-800	1	CFM56-7B26	Idle	n/a	17.6 ICAO: 18.80	1.2	1.9 ICAO: 4.70
B737-800	1	CFM56-7B27	Idle	n/a	25.7 ± 8.29 (17.3 - 33.8) ICAO: 17.90	0.7 ± 0.23 (0.4 - 0.9)	1.0 ± 0.35 (0.7 - 1.4) ICAO: 4.80
B737-8K2	3	CFM56-7B27	Idle	n/a	20.3 ± 8.37 (8.9 - 34.5) ICAO: 17.90	0.3 ± 0.24 (bdl - 0.6)	0.4 ± 0.37 (bdl - 0.9) ICAO: 4.80
B747-200	1	GE CF6-50E2	Idle	n/a	32.6 ICAO: type?	1.5	2.3 ICAO: type?
B747-236	3	RB211-524D4	Var	n/a	29.7 ± 30.75 (6.6 - 93.7)	2.1. ± 1.87 (0.1 - 4.6)	3.2 ± 2.87 (0.1 - 7.1)
B747-236	1	RB211-524D4	C	n/a	7.19 ± 0.17 (6.8 - 7.3) ICAO: 0.34	4.47 ± 0.11 (4.3 - 4.6)	6.85 ± 0.17 (6.5 - 7.0) ICAO: 43.01
B747-236	1	RB211-524D4X	Idle	n/a	26.0 ± 4.35 (21.0 - 31.2) ICAO: 9.30	bdl	bdl ICAO: 4.41

Table F-11: Continued.

Aircraft	No.	Engine type	N1 (%	Fuel flow (kg/h)	CO (g/kg)	NO (g/kg)	NOx (g/kg)
B747-436	7	RB211-524H2	Var	n/a	7.8 ± 5.92 (0.3 - 23.3)	2.3 ± 4.11 (bdl - 15.5)	3.5 ± 6.30 (bdl - 23.8)
B747-436	1	RB211-524H2	Idle	2520 ICAO: 936.0	12.2 ± 1.43 (10.4 - 13.4) ICAO: 11.75	0.2 ± 0.02 (0.2 - 0.3)	0.4 ± 0.04 (0.3 - 0.4) ICAO: 4.78
B747-436	1	RB211-524H2	C	n/a	0.43 ± 0.08 (0.3 - 0.5) ICAO: 0.38	8.46 ± 0.57 (8.2 - 9.9)	13.0 ± 0.87 (12.5 - 15.1) ICAO: 46.31
B747-436	1	RB211-524H2	TO	27720 ICAO: 9828	0.44 ICAO: 0.87	11.79	18.08 ICAO: 65.84
B757-236	1	RB211-535C	Idle	n/a	11.8 (11.7 - 12.0) ICAO: 18.79	0.5	0.7 ICAO: 3.44
B757-236	5	RB211-535C-37	Idle	639 ± 31 ICAO: 720	7.5 ± 2.10 (0.7 - 11.0) ICAO: 18.79	0.3 ± 0.17 (bdl - 0.6)	0.4 ± 0.27 (bdl - 0.9) ICAO: 3.44
B757-236	1	RB211-535E4	Idle	n/a	6.7 ± 0.12 (6.6 - 13.4) ICAO: 15.44	0.4 ± 0.07 (0.3 - 0.5)	0.6 ± 0.10 (0.5 - 0.7) ICAO: 4.30
B757-236	2	RB211-535E4-37	Idle	517 ± 22 ICAO: 684	9.2 ± 2.93 (5.5 - 13.4) ICAO: 15.44	bdl	bdl ICAO: 4.30
B767-336	1	RB211-524H-36	Idle	n/a	7.3 ICAO: 11.75	1.3	1.9 ICAO: 4.78
B777-236	7	GE90-85B	Var	n/a	27.7 ± 19.87 (2.2 - 64.1)	1.9 ± 2.01 (0.5 - 6.7)	3.0 ± 3.09 (0.8 - 10.3)
B777-236	2	GE90-85B	Idle	n/a	39.1 ± 24.62 (2.7 - 64.1) ICAO: 13.67	0.3 ± 0.27 (bdl - 0.5)	0.4 ± 0.42 (bdl - 0.8) ICAO: 5.69
B777-236	1	GE90-85B	A	n/a	18.2 ICAO: 1.10	0.8	1.3 ICAO: 16.73
MD-87	1	JT8D-217C	Idle	500 ± 0 ICAO: 493.2	10.3 ± 1.26 (9.4 - 11.2) ICAO: 17.89	bdl	bdl ICAO: 4.05
Fokker 70	10	RR-Tay MK 620	Idle	309 ± 9 ICAO: 396.0	23.1 ± 7.32 (11.5 - 46.7) ICAO: 24.10	0.2 ± 0.63 (bdl - 2.6)	0.3 ± 0.96 (bdl - 4.0) ICAO: 2.50
CRJ 100LR	1	GE CF 34-3A	Idle	n/a	39.2 ± 1.80 (38.0 - 40.5) ICAO: 42.60	0.7 ± 0.01 (0.6 - 0.7)	1.0 ± 0.02 ICAO: 3.82
CRJ 100LR	2	GE CF 34-3A1	Idle	n/a	36.7 ± 5.68 (31.0 - 46.6) ICAO: 42.60	0.6 ± 0.11 (0.5 - 0.8)	1.0 ± 0.16 (0.8 - 1.2) ICAO: 3.82
CRJ 200LR	8	GE CF 34-3B	Idle	182 ± 3	38.9 ± 11.75 (10.2 - 57.3)	0.7 ± 0.09 (0.5 - 0.9)	1.0 ± 0.13 (0.8 - 1.4)
DHC-8-300Q	8	PW 123B	Idle	301 ± 37	9.5 ± 6.63 (2.2 - 27.0)	1.1 ± 2.32 (bdl - 9.5)	1.7 ± 3.55 (bdl - 14.5)
DHC-8-400Q	5	PW 150A	Idle	370 ± 0	8.3 ± 3.84 (3.3 - 17.0)	0.6 ± 0.39 (bdl - 1.4)	0.8 ± 0.59 (bdl - 2.2)

F4.2 Auxiliary power units during ground operations

Mean values of emission factors of CO, NO, and NO_x from the APU´s of different aircraft during the winter and summer campaigns are given in **Table F-12**.

Table F-12: Results of APU-measurements ('bdl' = below detection limit). The minimum and maximum values of all measured data are given in brackets.

Aircraft	Number of aircraft	APU type	CO (g/kg)	NO (g/kg)	NO_x (g/kg)
A320-200	1	APS3200	2.9 ± 0.30 (2.5-3.1)	0.3 (bdl – 0.8)	0.4 (bdl – 1.3)
B737-406	1	APS2000	2.7 ± 0.29 (2.5 – 3.1)	1.7 ± 0.34 (1.4 – 2.2)	2.5 ± 0.53 (2.3 – 3.3)
B737-800	1	GTCP85-98DHF	13.9 ± 1.07 (12.4 – 15.1)	0.8 ± 0.07 (0.7 – 0.8)	1.2 ± 0.11 (1.0 – 1.3)
B747-236	1	GTCP660-4	2.2 ± 0.32 (1.9 – 2.4)	0.1 (bdl – 0.3)	0.2 (bdl – 0.4)
B747-400	3	PW901A	11.6 ± 3.98 (5.5 – 18.0)	1.1 ± 0.37 (0.6 – 1.8)	1.7 ± 0.56 (0.8 – 2.7)
B747-436	8	PW901A	12.4 ± 5.26 (0.5 – 31.3)	0.6 ± 0.75 (bdl – 2.7)	1.0 ± 1.14 (bdl – 4.2)
B757-236	3	GTCP331-200/250	1.1 ± 0.41 (0.2 – 1.7)	2.6 ± 0.79 (0.4 – 3.6)	3.9 ± 1.21 (0.6 – 5.5)
B777-236	3	GTCP331-500	1.3 ± 0.63 (0.5 – 2.2)	3.0 ± 0.87 (bdl – 4.5)	4.6 ± 1.33 (bdl – 6.9)

F4.3 VOC measurements

The VOC measurement procedure is given in Section F3.2, with the results given in **Table F-13**.

F4.4 Former Soviet aircraft

Emission factors for former Soviet aircraft were measured under real-world conditions (in-flight conditions) for different ages and after maintenance. Due to administrative and financial delays associated with the ARTEMIS project, Czyste Powirtrze were only able to deliver data for two aircraft: a Tupolev TU154 and a Jakowlew Jak-40. Some examples of the emission factors for the Tupolev TU154 are shown in **Figures F-4** to **F-6**.

F4.5 In-flight emissions

The results of these measurement campaigns showed that real-world emission data do not correspond to the emission factors under standard conditions which are published in the ICAO database, and upon which most of the emission calculation methodologies are based. This was observed for engine age as well as for weather conditions.

Only a small number of different aircraft types were measured within the final ARTEMIS programme. Further real-world measurements are recommended in order to produce a reliable emission calculation methodology.

Table F-13: VOC measurement results.

Sample	S1	S2	S3	S6	S7	S10	S4	S9
Sampling conditions	During ignition	During ignition	During ignition	During ignition	During ignition[a]	No aircraft movements	During ignition	Diesel motors running
CO [ppb]	369	547	616	597	561	621	532	1037
Ethane	4527	10217	9227	9257	9234	9244	7184	8097
Ethene	5440	3682	7183	5923	3894	5218	4652	26608
Ethyne	3317	3222	3825	3368	2937	3499	2636	9206
Propane	2261	4196	4743	5049	5074	4947	3643	3754
Propene	1442	1097	1877	1575	1092	1391	1193	6748
i-butane	1016	2267	2464	2464	2919	2866	1969	1951
Butane	1813	4395	4853	4772	6458	5556	3397	3413
Propyne + 1-Butene	262	182	291	260	189	337	217	1292
1,3-butadiene	335	136	282	207	119	260	135	1335
Trans-butene	146	242	242	230	343	254	162	413
i-butene	205	290	436	276	256	363	166	813
Cis-butene	105	179	179	160	185	166	125	325
3-M-1-butene	57	55	76	90	71	71	48	257
i-pentane	2288	4632	5526	5047	7346	5223	3528	3135
1-pentene	206	144	260	227	170	168	126	1146
2-M-1-butene	130	206	222	219	232	195	144	423
Pentane	722	1806	3319	2759	4828	2273	1475	1418
Isoprene	119	133	176	165	89	102	106	416
Trans-pentene	154	204	264	183	190	165	104	234
Cis-pentene	64	112	136	158	108	108	85	158
2-M-2-butene	98	293	240	242	236	204	135	160
2,2-DM-butane	473	699	698	739	774	754	491	835
Cyc-pentene	49	50	56	71	51	53	35	193
4M+3M-pentene	68	56	51	74	56	70	40	244
2,3-DM-butane	92	208	368	318	557	283	172	163
Cyc-pentane	195	392	517	469	734	481	269	300
2-M-pentane	827	1406	2234	1894	3216	1771	1041	929
3-M-pentane	340	747	1338	1097	2041	913	504	456
2-M-1-pentene	165	125	216	170	146	156	128	919
Hexane	338	809	2484	1836	4237	1177	569	651
c-3-Hexene	Bdl	43	28	32	33	46	23	32
t-2-Hexene	23	55	49	41	39	55	33	78
c-2-Hexene	15	60	28	35	29	29	25	44
M-cyc-pentane	230	556	1493	1105	2546	847	397	367
2,4-DM-pentane	107	109	229	168	305	141	88	143
Benzene	1200	1735	2124	2028	2500	1939	1484	2842
Cyc-hexane	191	522	1639	1146	2795	852	387	404
2-M-hexane	321	382	1520	1092	2280	697	414	376
2,3-DM-pentane	201	262	699	520	1039	371	253	213
3-M-hexane	200	502	1874	1343	3072	843	387	313
2,2,4-TM-pentane	298	580	1253	969	1782	705	443	662
Heptane	196	642	4076	2680	6992	1188	385	388
2,3-DM-2-pentene	9	68	149	66	18	10	10	27
M-cyc-hexane	176	620	4471	2885	8188	1354	339	439
2,3,4-TM-pentane	131	165	546	189	888	184	162	183
Toluene	2003	4469	6054	5608	8606	5676	3066	3377

a Engines of second aircraft running

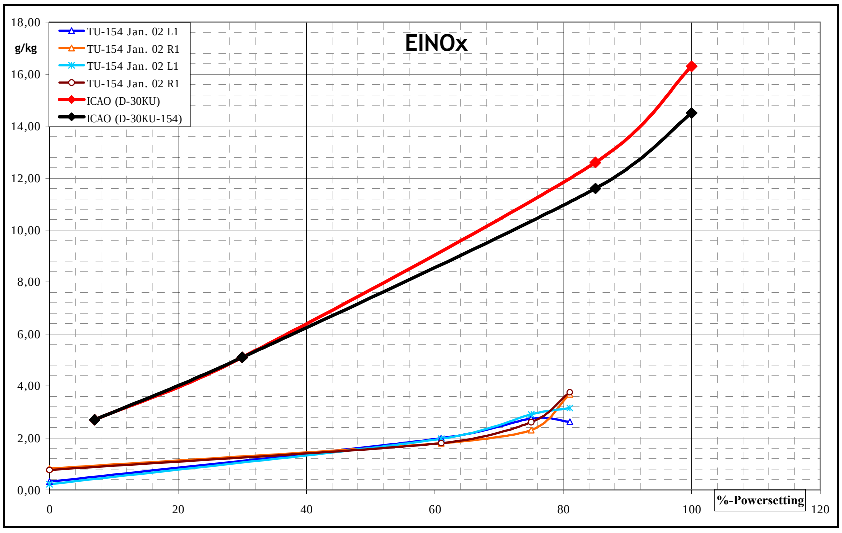


Figure F-4: NO_x emission factors (TU154).

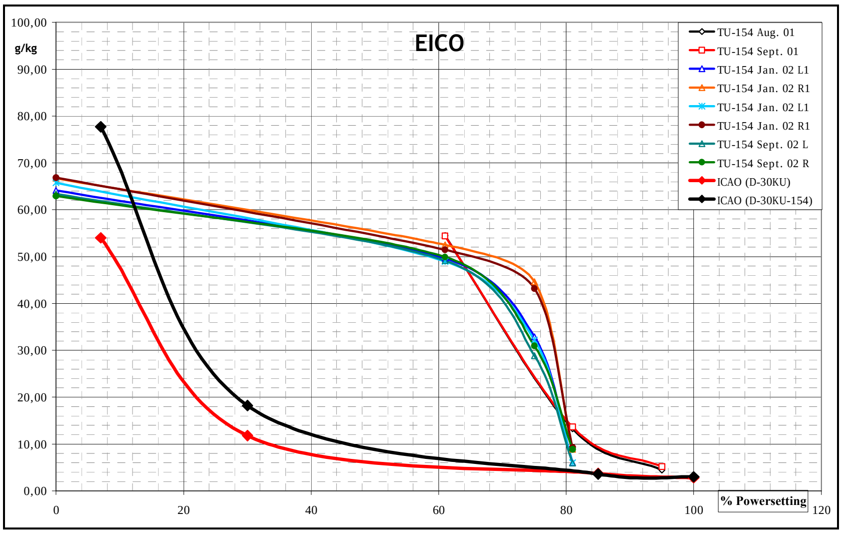


Figure F-5: CO emission factors **(**TU154).

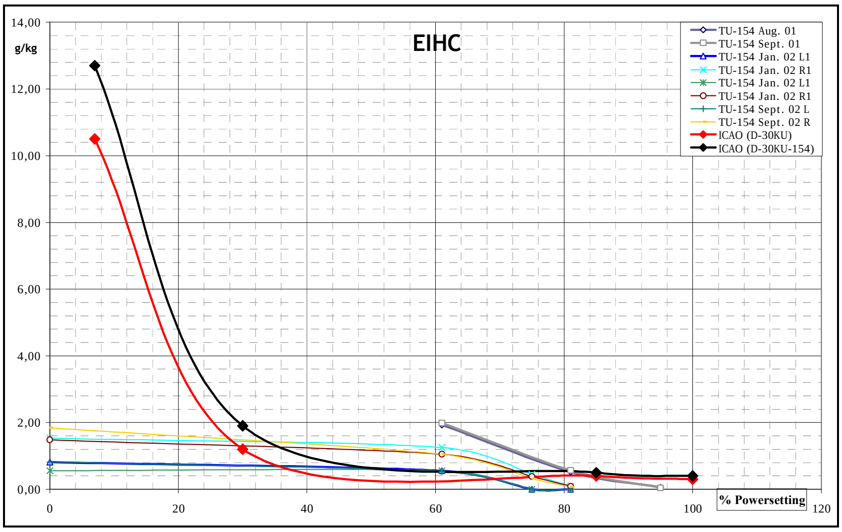


Figure F-6: HC emission factors (TU154).

F4.6 Ageing of engines

For the two former Soviet aircraft types Tupolev TU154 and the Jakowlew Jak-40 the dependency between the height of the emission factors and the operational hours was derived. The results are summarized in **Figures F-7** and **F-8**.

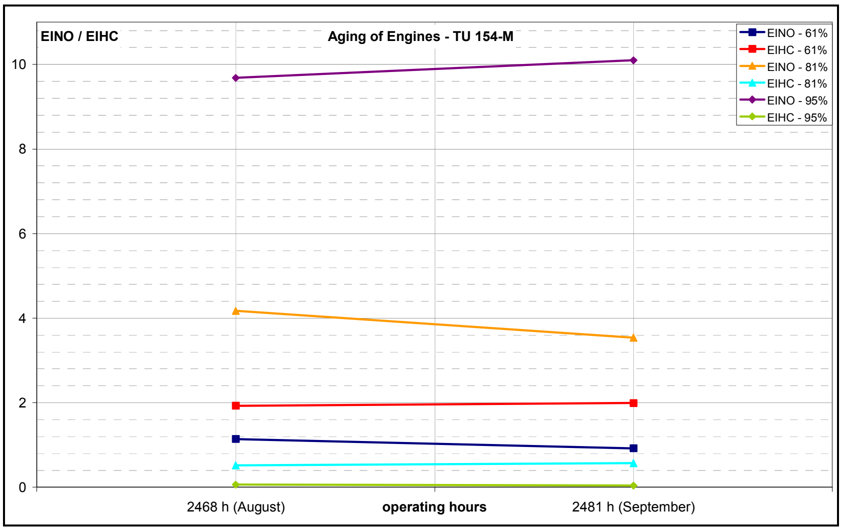


Figure F-7: Ageing of engines (TU154M).

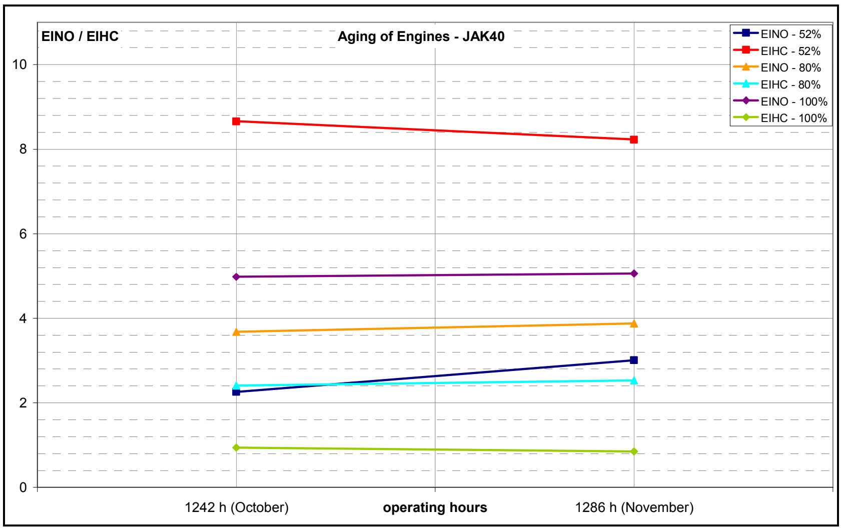


Figure F-8: Aging of engines (JAK40).

F5 ARTEMIS modelling approaches

F5.1 Turboprop aircraft

The representation of turboprop aircraft is currently relatively poor, since turboprop engines are not included in the ICAO engine exhaust emission databank. FFA has considerable experience in modelling turboprop emissions, and has generated, with the support of engine manufacturers, an emission database to create fuel consumption and emission factors that fit into the existing MEET emission data scheme. These data have been used in the recent update of the UNECE Guidebook.

A database model for studying emissions during different phases of an aircraft flight profile, from taxi-out, through the main profile, to taxi-in, has been created. This model can be distributed to external users, in which case the data for the aircraft and their performance characteristics are stored in an fixed form, and the user can control the taxi time, the cruise altitude, and the total flight distance.

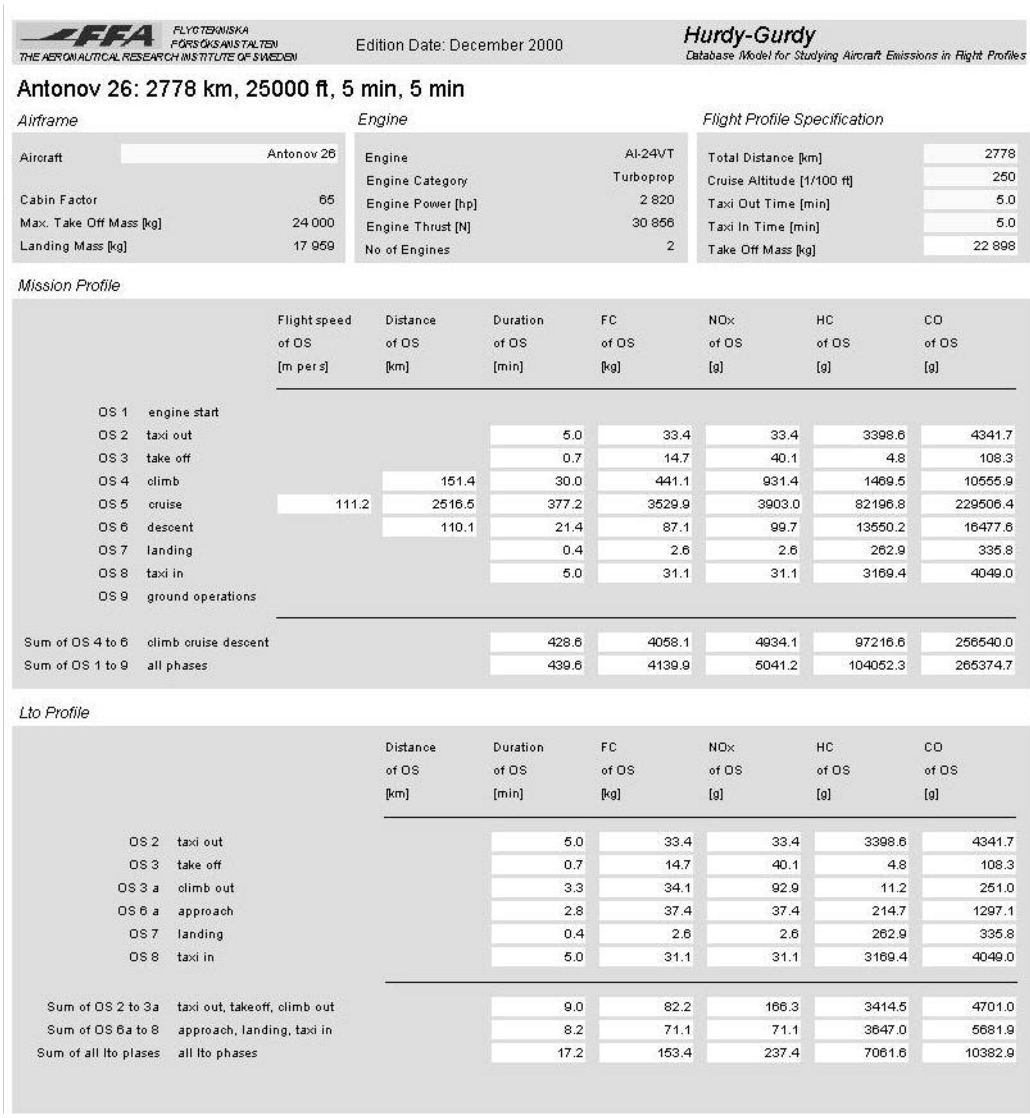
Both the model and the supporting data reside in FileMaker®, a database manager. The modelling is based on a number of functions which have been carefully selected to reflect the nature of the parameter variability in each case. The coefficients of the functions are aircraft-dependent. Currently, the model includes function coefficients for 23 types of turboprop aircraft.

The database model uses pre-processed aircraft data derived from external sources, such as the results from PIANO (Simos 2000) and HARP, available from FFA (Hasselrot, 2001).

The modelling has to be detailed enough to reflect the various segments of the whole flight procedure, from taxi-out until taxi-in. The user is able to choose any altitude between sea level and the ‘ceiling’ that is practically attainable, and any distance up to the maximum range with regard to the available fuel. In addition, the user is able to specify the duration of taxi-out and taxi-in. This had to be achieved without compromising the reliability of the computed fuel consumption and emissions.

The wide range of values for the independent parameters cruise altitude and flight distance necessitated the careful selection of model functions to minimise the total number of function coefficients. Two sources, available from FFA, were selected for creating the emission data: PIANO for the journey profile (climb, cruise, and descent) and HARP for the LTO cycle (taxi-out, take-off, climb-out, approach, landing, and taxi-in). The emission indices from these two methods were taken from the ICAO databank, or from other sources where data are presented in the ICAO format.

The database model, together with the turboprop aircraft data, uses specific function coefficients for each aircraft. These coefficients have to be analysed by using reference data from software runs with PIANO and HARP. To facilitate this, a semi-automatic procedure in has also been created FileMaker, and this ensures that it is very easy to check the validity of the function coefficients. In this way, total values of distance, time, fuel consumption, and emissions can be compared. This database model has been named ‘Hurdy-Gurdy’. An example of a user-created record in the model is shown in **Figure F-9**.


FLYGTEKNISKA FÖRSÖKSANSTALTEN
THE AERONAUTICAL RESEARCH INSTITUTE OF SWEDEN
Edition Date: December 2000
Hurdy-Gurdy
Database Model for Studying Aircraft Emissions in Flight Profiles

Antonov 26: 2778 km, 25000 ft, 5 min, 5 min

Airframe

Aircraft	Antonov 26
Cabin Factor	65
Max. Take Off Mass [kg]	24 000
Landing Mass [kg]	17 959

Engine

Engine	AI-24VT
Engine Category	Turboprop
Engine Power [hp]	2 820
Engine Thrust [N]	30 856
No of Engines	2

Flight Profile Specification

Total Distance [km]	2778
Cruise Altitude [1/100 ft]	250
Taxi Out Time [min]	5.0
Taxi In Time [min]	5.0
Take Off Mass [kg]	22 898

Mission Profile

		Flight speed of OS [m per s]	Distance of OS [km]	Duration of OS [min]	FC of OS [kg]	NOx of OS [g]	HC of OS [g]	CO of OS [g]
OS 1	engine start							
OS 2	taxi out			5.0	33.4	33.4	3398.6	4341.7
OS 3	take off			0.7	14.7	40.1	4.8	108.3
OS 4	climb		151.4	30.0	441.1	931.4	1469.5	10555.9
OS 5	cruise	111.2	2516.5	377.2	3529.9	3903.0	82196.8	229506.4
OS 6	descent		110.1	21.4	87.1	99.7	13550.2	16477.6
OS 7	landing			0.4	2.6	2.6	262.9	335.8
OS 8	taxi in			5.0	31.1	31.1	3169.4	4049.0
OS 9	ground operations							
Sum of OS 4 to 6	climb cruise descent			428.6	4058.1	4934.1	97216.6	256540.0
Sum of OS 1 to 9	all phases			439.6	4139.9	5041.2	104052.3	265374.7

Lto Profile

		Distance of OS [km]	Duration of OS [min]	FC of OS [kg]	NOx of OS [g]	HC of OS [g]	CO of OS [g]
OS 2	taxi out		5.0	33.4	33.4	3398.6	4341.7
OS 3	take off		0.7	14.7	40.1	4.8	108.3
OS 3 a	climb out		3.3	34.1	92.9	11.2	251.0
OS 6 a	approach		2.8	37.4	37.4	214.7	1297.1
OS 7	landing		0.4	2.6	2.6	262.9	335.8
OS 8	taxi in		5.0	31.1	31.1	3169.4	4049.0
Sum of OS 2 to 3a	taxi out, takeoff, climb out		9.0	82.2	166.3	3414.5	4701.0
Sum of OS 6a to 8	approach, landing, taxi in		8.2	71.1	71.1	3647.0	5681.9
Sum of all lto plases	all lto phases		17.2	153.4	237.4	7061.6	10382.9

Figure F-9: An example of user-created record, containing a selected aircraft and specified flight parameters (Hasselrot, 2001).

F5.2 Auxiliary power units

Overview

The aim of the ARTEMIS APU emission model was to provide emission factors for the ground operation of APU engines, to apply these to existing air traffic activity data, and to develop a database of environmental indication for air transport, including forecasts (Kalivoda and Bukovnik, 2007).

Some specific air transport emission models like LASPORT[65], and airports such as Zurich, use APU emission data for aircraft types. Aircraft statistics from Eurocontrol for the most frequently used aircraft types in 1998, 1999 and 2000 were used to provide input data for the development of the ARTEMIS APU emission model. The model was developed as a possible extension of the TRENDS methodology, and emission data were generated for the years 1970 to 2015.

Aircraft selection

The selection of aircraft types for the model was dependent upon the availability of APU emission data for specific aircraft. For the APU emission model around 80% of all aircraft types used in Europe were covered. **Table F-14** shows the aircraft used in the emission model. Aircraft with no APU on board are assumed to have zero emissions.

Table F-14: Aircraft used in the ARTEMIS APU emission model.

Aircraft type	Aircraft type	Aircraft type
AIRBUS A-300B2/4	BEECH 1900 (C-12J)	FOKKER 70
AIRBUS A-300B4-600	BEECH 90	FOKKER F-28
AIRBUS A-310 (CC-150	BOEING 727-200	GULFSTREAM 4
AIRBUS A-319	BOEING 737-200	LEARJET 35/36
AIRBUS A-320	BOEING 737-300	MD-11
AIRBUS A-321	BOEING 737-400	MD-80-Series
AIRBUS A-330	BOEING 737-500	PA28-140/161/180/181
AIRBUS A-340	BOEING 737-800	RJ-100 REGIONAL JET
ATR-42-200/300/320	BOEING 757-200	RJ-200 REGIONAL JET
ATR-42-500	BOEING 767-300	SAAB 2000
ATR-72	BOEING 777-200	SENECA III PA34-220T
AVRO 748 (C-91)	CHEROKEE	SF 340
BAE146-100/200/300	D328	SHORTS 360
BAE-3100	EMBRAER EMB-145	TUPOLEV TU-134
BAE-3200	FOKKER 100	TUPOLEV TU-154
BAE-4100	FOKKER 50	

Aircraft movements and forecasts

There are significant difference between aviation and other modes of transport in relation to the availability of activity data. For road transport national figures for kilometres per year and global assumptions on driving behaviour are used. Air transport, on the other hand, is controlled by air traffic control services, which report each flight within or crossing European airspace to Eurocontrol. Information is therefore available for all the flights in Eurocontrol area, the profile flown, and aircraft type used. This makes it possible to use a bottom-up approach when estimating emissions from civil aircraft.

The aircraft movement data used in the ARTEMIS APU emission model were derived from the TRENDS TABS model, and the results can therefore be implemented in the TRENDS model. Additional activity data were taken from the AEA technology database (for 1975-1995) and from Eurocontrol STATFORE (for 2002-2015). STATFORE is updated annually, and contains the number of movements per region and country, with a forecast up to 2015. In order to produce emission forecasts for the time period 2002-2020, the traffic increase rates between 2002 and 2009 predicted by Eurocontrol were extrapolated up to the year 2020.

APU emission calculation

Within the TRENDS database there are two main approaches:

- AvioPOLL: 1996-2002
- TAB: 1970-2020

[65] http://pandora.meng.auth.gr/mds/showlong.php?id=153&MTG_Session=cc401c1139cca2154c8fb44124a565c4

The activity data which feeds into AvioPOLL are the aggregated numbers of flights for origin/destination pairs per aircraft type. It is not possible to change a given origin/destination pair for one aircraft type into another type in order, for example, to assess the impact on the environment of certain transport planning policies. A particular module within TRENDS deals with the 'balance of overall transport activity data' (TAB). TAB cover a time period from 1970 to 2020, and allows the definition of activity and emission scenarios. TAB also allows the user to perform a simple scenario analysis by assessing the effects of different assumptions about key factors like transport activity evolution, modal shifts, different emission standards, *etc*. Varying some key factors leads to the creation of alternative scenarios. It is up to the user to define 'reasonable' variations of the assumptions. This should be possible for the time period from 1970 up to 2020, (on a yearly basis) according to the time frame covered by TRENDS. The appropriate level of spatial allocation is the country level or the EU. The traffic activity and emission data produced by TAB can be displayed according to the traffic type (passenger/freight), according to the vehicle type and the vehicle technology.

The APU emission data were derived in such a way that they could be implemented in the TRENDS database. For a single flight within Eurocontrol area the APU emission factors are shown in **Table F-15**.

Table F-15: APU emission factors for a flight in the Eurocontrol area.

Average emissions per movement			
Fuel (kg/h)	HC (g)	CO (g)	NO_x (g)
114.88	57.36	962.65	756.06

APU data were produced for a time period from 1970 up to 2015. Emissions were generated per year and country according to the Eurocontrol definitions of short-haul, medium-haul and long-haul.

F6 Conclusions

Throughout the ARTEMIS project, existing measurements and databases for in-flight emissions arising from the European Commission aeronautic research projects proved difficult to access. The European Community Shared Environmental Information System (SEIS), designed to allow and facilitate the European dissemination of relevant environmental data, combined with the INSPIRE Directive (2007/2/EC) which came into force during May 2007, could assist in improving future access to environmental information.

However the ARTEMIS programme evaluated data from the ICAO emission database and supplemented and compared these data with new in-service measurements from Frankfurt-Main, Vienna-Schwechat, London Heathrow and Wroclaw airport. Results of these measurements indicated that real life emissions are different from emission measured over standard conditions. This can result in significantly different results in emission calculations.

Emissions from engine start are not included in the conventional LTO cycle modelling, but have a significant influence on total emissions and local air quality around airports. In the first step of this task a common methodology was developed to measure NO_X, NO_2, N_2O, CO, HC, CH_4, SO_2, PM_{10} and $PM_{2.5}$ emissions from aircraft engines, whilst on the ground. The work incorporated IFU's experience in air traffic emission measurements and involvement and interaction with other projects, such as AEROCERT and AEROJET. Both of these projects dealt with the improvement of measurement techniques. Improved non-intrusive measurement methods such as FTIR developed in AEROJET 2, were employed and further developed. To validate the whole system, intrusive measurements and engine test bed measurements were also undertaken.

Based on explorative measurements at Frankfurt and Heathrow airport, enhanced measurements were made at Vienna and a second campaign at Heathrow Airport. The main objective of these measurements was to test the data collection procedure in relation to the operational requirements of the airports. The calibration of the measurement procedure was achieved through the use of a series of measurements undertaken on a burner unit, used to simulate an exhaust jet plume. A second explorative measurement campaign was undertaken in Aachen, Germany on a real aircraft engine. The main objective of these measurements was to retest the data collection which was made at the measurements at Vienna Airport in autumn 2001 and to improve with these two experiences the measurement procedure in relation to the operational requirements for the winter campaign of measurements at Vienna Airport. These explorative measurement campaigns lead to the development of comprehensive measurement campaigns at Heathrow and Vienna Airports.

A second tranche of measurements were made on the most commonly used engines in Europe, under different ambient conditions (summer/winter, dry/wet) for different engine ages and maintenance (new/old, before/after overhaul) levels, for engine start up and different power settings (LTO cycle).

Finally these new measurements were used to create a revised set of emission index (EI) for the additional start up emissions as well as support for the creation of in flight emission factors.

The ARTEMIS programme may thus be considered one of the first steps towards the development of real world aircraft exhaust emission measurements. Unfortunately, due to a lack of data from the aircraft operators on specific power settings during measurement campaigns, these data were not fully used for the generation of the emission estimation methodology.

The participation of FFA within the ARTEMIS programme, gave access an insight into the FFA software tool, which allows the simulation of emissions from 23 different turboprop aircraft.

Currently the emission inventory tools focus on aircraft used in Western Europe. However, within the Eurocontrol area about 400 to 500 aircraft movements per day, or about 2% of the traffic, are still operated by aircraft originating from the former USSR fleets. Measurements on two Eastern European aircraft were undertaken at Wroclow, under different ambient conditions for engine start up and the LTO cycle. Data were used to create a set of emission indices for start up emissions and in flight emission factors. However, even in Poland the proportion of former Soviet aircraft is low. In general the movement of former Soviet aircraft across Western Europe airports, amounts to about one to five aircraft per week.

Finally, the ARTEMIS aircraft work used the TRENDS air traffic methodology and database as the basic modelling platform. The ARTEMIS work may thus be seen as an extension to this pre-existing tool. The work focussed on the 40 most relevant aircraft/engine combinations used in Europe, representing about 85% of European instrumented flight rules (IFR) flights. The project extends basic knowledge on NO_X, CO and HC species, and allowed the inclusion of preliminary measurements on species such as methane, particulate matter and NO_2 within the aircraft emission database. Significant measurements on APUs were undertaken and incorporated within the TRENDS database model.

Finally the TRENDS model was extended to include some insight into emissions and fuel consumption associated with the newest aircraft technologies and changes in the fleet mix. This will allow improvements in the use of the TRENDS model for the estimation of future emissions. to allow the assessment of transport scenarios and policies over a 20 year time frame.

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PART G: INVENTORY MODEL

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G1 Overview

In ARTEMIS the emission models for the various transport modes were converted into computer programs. The level of software development varied considerably according to the transport mode. By far the most detailed software package was produced for road transport. Less sophisticated packages were produced for rail transport, air transport and shipping. The following Sections describe the software tools which were developed.

G2 Road transport model

G2.1 Introduction

Overview

The description of the road transport model preseted here is taken from the report by Keller and Kljun (2007a). More details on the use of the model are provided in a separate User Guide which has been produced to facilitate the handling of the model (Keller and Kljun, 2007b).

The ARTEMIS road transport model basically contains of an emission factor database and several procedures to calculate emissions. However, the calculation of emissions requires many situation-specific inputs which describe the traffic at a particular point in time. The road model contains the following elements:

- An **emission factor database**. The emission factors are based upon the emission measurements performed within the ARTEMIS project, but also upon other, mainly national, sources.
- A **fleet model**. This model allows the user to set up the necessary fleet composition for a particular country (for one or several years).
- An **emission factor module**. This module allows access to the emission factor database and, in particular, it calculates *weighted emission factors* for particular traffic situations (again, for a particular country, and for one or several years) using the user-specified fleet composition from the fleet model.
- An **emission model**. This model calculates the overall emissions - either on an aggregate basis for a particular country, region or city, or for a specific network (*i.e.* on link-by-link basis). For these calculations the model again refers to the user-specified description of the fleet and the traffic activity, in combination with the emission factors.

Figure G-1 gives an overview of the different elements of the model. The model mainly requires a traffic description (fleet composition and traffic activity data), plus some additional information on local characteristics (such as temperature distributions and fuel quality descriptions). This means that the model needs many user-specified inputs. However, it contains default values for many parameters, but it is recommended that local input data are used where possible.

The model is designed in such a way that it allows emissions (or weighted emission factors) to be calculated for a single year as well as for time series between 1980 and 2030. This means that the model contains emission factors for most relevant vehicle concepts in the past, as well as the most recent ones, and makes assumptions about the emission behaviour of future vehicles. The emission factors for existing vehicles are based upon emission measurements. The emission factors for new and future concepts are based upon assumptions made within ARTEMIS. Furthermore, the model is designed to calculate the effects of scenarios (whereby input data have to be assigned to the scenarios).

The ARTEMIS road model contains – as far as possible – the results from the different aspects of the ARTEMIS and COST 346 projects, with the idea of providing users with structured access to the huge variety of data measured, collected and analysed. However, it was also the intention to provide:

(i) A method of determining *weighted emission factors for the fleet* (such as in the DACH-Handbook of Emission Factors).

(ii) A tool for *calculating emissions* (as in COPERT, for example).

In both cases, the user has to specify a fleet composition for the case (time, area) of interest, and additional information relevant information (*e.g.* ambient temperatures).

If there is a need to calculate emissions, it is obvious that the user has to specify the full set of traffic activity data (either on an aggregate level (*e.g.* nationwide), or on a network level for a set of individual roads. This means that the user has to start by providing inputs before he or she obtains results, even if there is only a requirement for simple emission factors.

Objectives

The main objective of the ARTEMIS road model was to put together a detailed methodology for the calculation of all types of emission from road transport, and to transfer the method into a menu-driven, user friendly computer program. A basic requirement (and key element) was the internal consistency of the model when applied at different levels of spatial resolution. In particular, the methodology – transferred to the emission model – takes into account the structure of the new emission factors from ARTEMIS, as well data from other national and international studies.

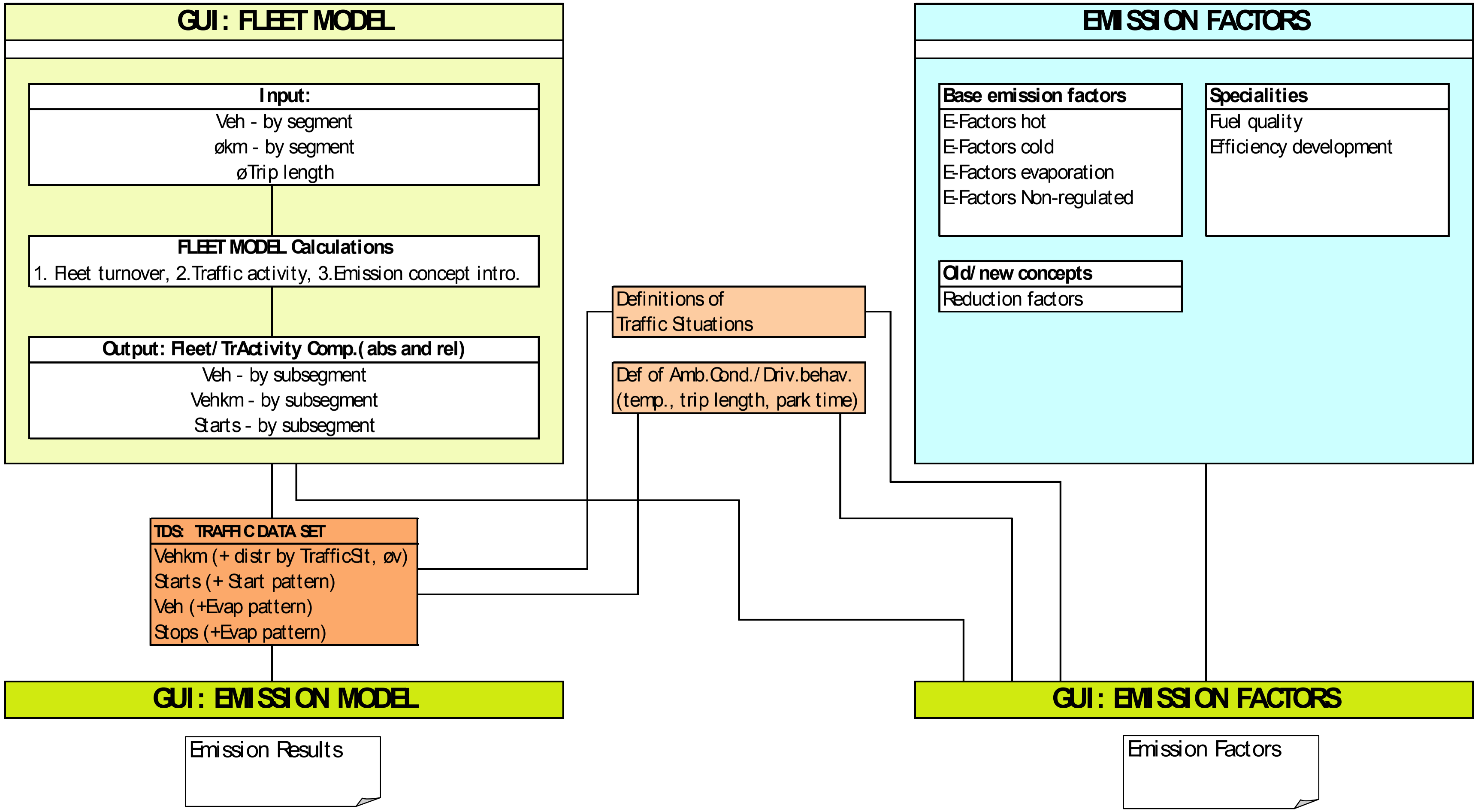


Figure G-1: Overview of the ARTEMIS road emission model (Keller and Kljun, 2007a).

The driving forces behind the development of such an emission model include: (i) the regulatory tasks aiming at reducing the environmental load due to pollutant emissions as well as greenhouse gas emissions, (ii) evaluations of projects, programmes and measures, and (iii) reporting mechanisms (like CORINAIR, TERM) describing the status and development of the environment. These can be translated into different forms of applications of emission models, such as:

- Classical emission inventories at different levels of spatial resolution (regional, national).
- Scenario calculations, making assessments of the impacts of alternative developments or measures.
- Providing inputs to air quality models which have the same or similar objectives in describing and assessing the quality of the environment as tools for corresponding policies.

The ARTEMIS emission model was designed with these types of applications in mind. In particular, it was decided that it had to users access to emission factors in a flexible way, and at the same time the user had to be able to calculate emissions on an aggregated level (*e.g.* regions, nations). In addition, the model had to allow for applications at the street level and provide inputs for air quality models.

Approach

The basic approach underlying emission calculations is comparatively straightforward (*i.e.* emissions are a product of activity data and emission factors). However, since emission factors, as well as the types of emission) vary to a large extent, the crucial point is the 'segmentation' of the calculation in several dimensions, such as:

- The classification of the fleet, since it is known that different generations of vehicles and technologies emit considerably different amounts of pollutants.
- The types of pollutant. Some pollutants are regulated, and hence it is of interest to know their behaviour in reality, whereas others are not regulated but nevertheless have direct harmful impacts or contribute to the formation of secondary pollutants, that might have a more detrimental impact, and thus justify their assessment.
- The operational conditions. This refers to different driving behaviour for different traffic situations, and also to particular situations or effects like cold-start and evaporative emission characteristics.
- The temporal resolution (hour, day, year). The prime focus here is the daily calculation of emissions, allowing further disaggregation down to the hour level (thus allowing input into air quality models), and aggregation to the year to provide indicators for inventories.
- The development of emissions over time. In addition to punctual information about the emissions at one particular point in time, it is a prime interest to make assessments over a certain time period, since most technical measures (normally induced by legislation) will only show their effect over time. Therefore, the model was designed to allow the calculation of 'emission scenarios' (*i.e.* time series over several years).
- The spatial resolution. The model had to be suitable for both aggregate and 'link-based' applications.

Caveats

When implementing the information from the different parts of ARTEMIS, it soon became clear that additional measurements (other than from ARTEMIS and COST 346) would also have to be taken into consideration in order to allow emission calculation for a full fleet and for full time series. Since measurement techniques and methodologies change over time, it is often not obvious how these different sources can be pulled together, and in general transformation procedures are required to arrive at a dataset which is, as far as possible, consistent. The present ARTEMIS model (considered a 'Beta' version) does fulfil these requirements to a large extent. Nevertheless, there are areas where – despite considerable effort by the responsible consortium partners – only a partial set of emission factors could be provided and which could not be completed by the modellers. In other areas, different views were expressed by different modellers, and therefore alternative approaches were provided. The users of the model should therefore be aware of its limitations, in particular:

- The limited availability of emission factors for some vehicle types (the model provides tools for checking availability).
- Some inconsistencies (*e.g.* different average speeds for the same traffic situation for LDVs, HDVs and two-wheel vehicles).
- Different approaches with diverging emission factors for basically the same phenomena (*e.g.* two models representing two sets of emission factors for passenger cars and light commercial vehicles).
- Differences in the reliability of the emisson factors based on limited measurements (*e.g.* there were comparatively few for light commercial vehicles).
- Emission factors of many non-regulated pollutants are available for selected vehicle groups only, which prevents the calculation of some specific emissions from a fleet.

G2.2 The fleet model

Objective

The fleet model produces the description of the traffic activity at the necessary level of detail for the emission calculation. This result is produced and saved as a ‘traffic scenario’. A ‘traffic scenario’ implicitly defines the fleet composition for any year, differentiated by ‘subsegments’ and by road categories (see **Figure G-2**). The drawing of a straight vertical line for any year in **Figure G-2** gives the relative fleet composition for that year. The model produces absolute values (vehicle-kilometres, vehicles), and also relative values. Often, only the relative values are of interest (*e.g.* where weighted average emission factors are required). The vehicle-km values will be used for calculating hot exhaust emissions, whereas the number of vehicles is needed for calculating evaporative emissions.

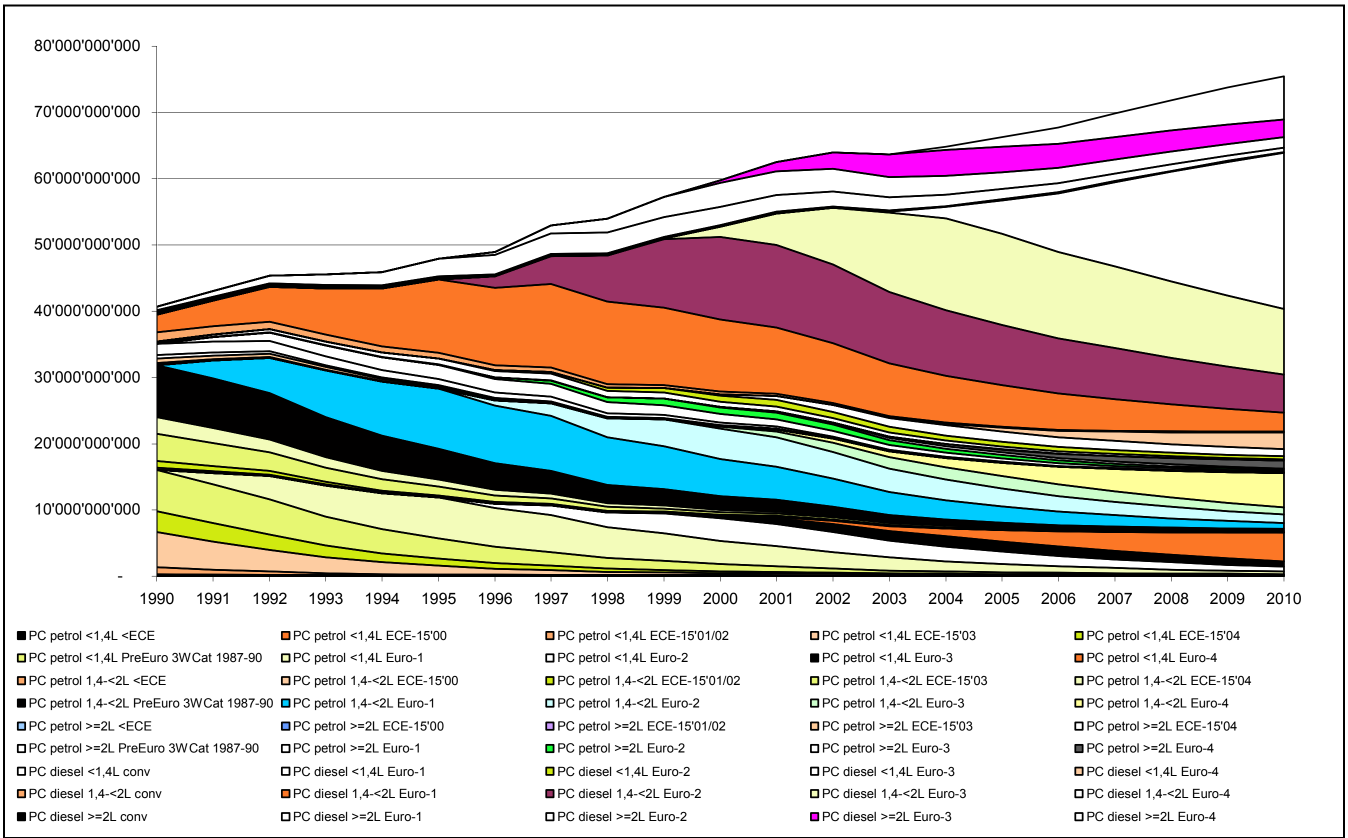


Figure G-2: Description of traffic activity. The example is for passenger cars in Austria, with vehicle.kilometres (*y*-axis) by sub-segment. (Keller and Kljun, 2007a).

Structure of the fleet model

Figure G-3 illustrates the structure of the ARTEMIS fleet model. The ARTEMIS model (and the fleet module in particular) is designed in such a way that several scenarios can be assessed. The user is requested to build the scenarios, and consequently every data set will belong to a scenario. In the case of the fleet model, the user must build a ‘traffic scenario’.

A traffic scenario is a composite of three sub-scenarios:

- A fleet scenario.
- A traffic activity scenario.
- An emission concept scenario.

Each of these sub-scenarios requires specific input data.

The fleet scenario is defined as follows:

- For past years: number of vehicles and age distributions according to statistical data (*e.g.* vehicle registrations).

- For future years: the module calculates the fleet turnover, based on assumptions about future new registrations and survival rates.

The traffic activity scenario is defined by:

- Mileage (km/year and vehicle).
- Distribution of the mileage between road categories.
- Age dependency of the mileage.
- Load patterns.

The emission concept scenario is defined by:

- The introduction of the technical concepts (*e.g.* Euro II cars entered the market between 1996 and 2001, Euro III between 2001 and 2005, *etc*.).

Implementation principles

Time series and number of years

The model is designed for the calculation of time series. Therefore, the user must specify the time period by setting a 'start year' (>=1980), a 'base year' (or reference year) - *i.e.* the year with the most recent statistical data, and an 'end year' (<= 2030). If the user can to specify or obtain information for one particular year only, then it is appropriate to set the start year, the base year, and the end year to be equal.

Country-specific data

Whilst many traffic definitions (and emission factors) are not country-dependant, all user-specific input is country-dependent. Therefore, the ARTEMIS emission model treats each country separately. The user must firstly select the country to be modelled, and must then add data for the selected country. However, it is possible to select (and store) data for several countries in the same database, and by changing the country selection it is possible to access the different data sets. It is also possible to copy data from one country to another. Furthermore, the user is free to add countries.

Top-down approach within the fleet model

The fleet model requires one value per vehicle category and year (*e.g.* number of passenger cars and km/year, and vehicles in year X). The subsequent distribution between vehicle segments is based upon relative distributions (splits) and not by absolute numbers (*e.g.* the vehicle stock contains x% small petrol cars, y% medium-sized petrol cars, *etc.*).

Road categories

The emission model, and hence the fleet module, distinguishes – as in many aggregate emission models – between three road categories (motorway, rural, urban). Operationally, a top-down approach is used here as well. As for the differentiation by segments, the data at the top level (*e.g.* the overall mileage) can be split between the road categories by assigning relative proportions.

Data pool and scenario building

The model distinguishes between the following:

- A 'data pool', in which all independent data sets are saved,
- A 'scenario building process' for defining fleet composition at the necessary level of detail.

Examples of these include:

- Vehicle age distributions (or any other distributions) are, in principle, generic, but will be saved under a specific name in the data pool.
- A fleet scenario describes the fleet of a country (for one or several years, and for one or several vehicle categories) and is a composite of descriptions of the vehicle stock, of proportions by segment, of corresponding age distributions, *etc*. A fleet scenario is an independent entity, and hence is part of the data pool. During the scenario building process the user selects a fleet scenario and calculates the vehicle turnover.
- Similarly, a traffic activity scenario is an independent but composite entity, describing the mileage per vehicle (again, for one or several years, and for one or several vehicle categories) including additional parameters such as age dependency of the mileage. Since it is an independent entity it is also part of the data pool. During the scenario building process the user selects a traffic activity scenario (mileage per vehicle) and a fleet scenario (vehicle stock) in order to build a composite traffic scenario (vehicle-kilometres of a fleet).

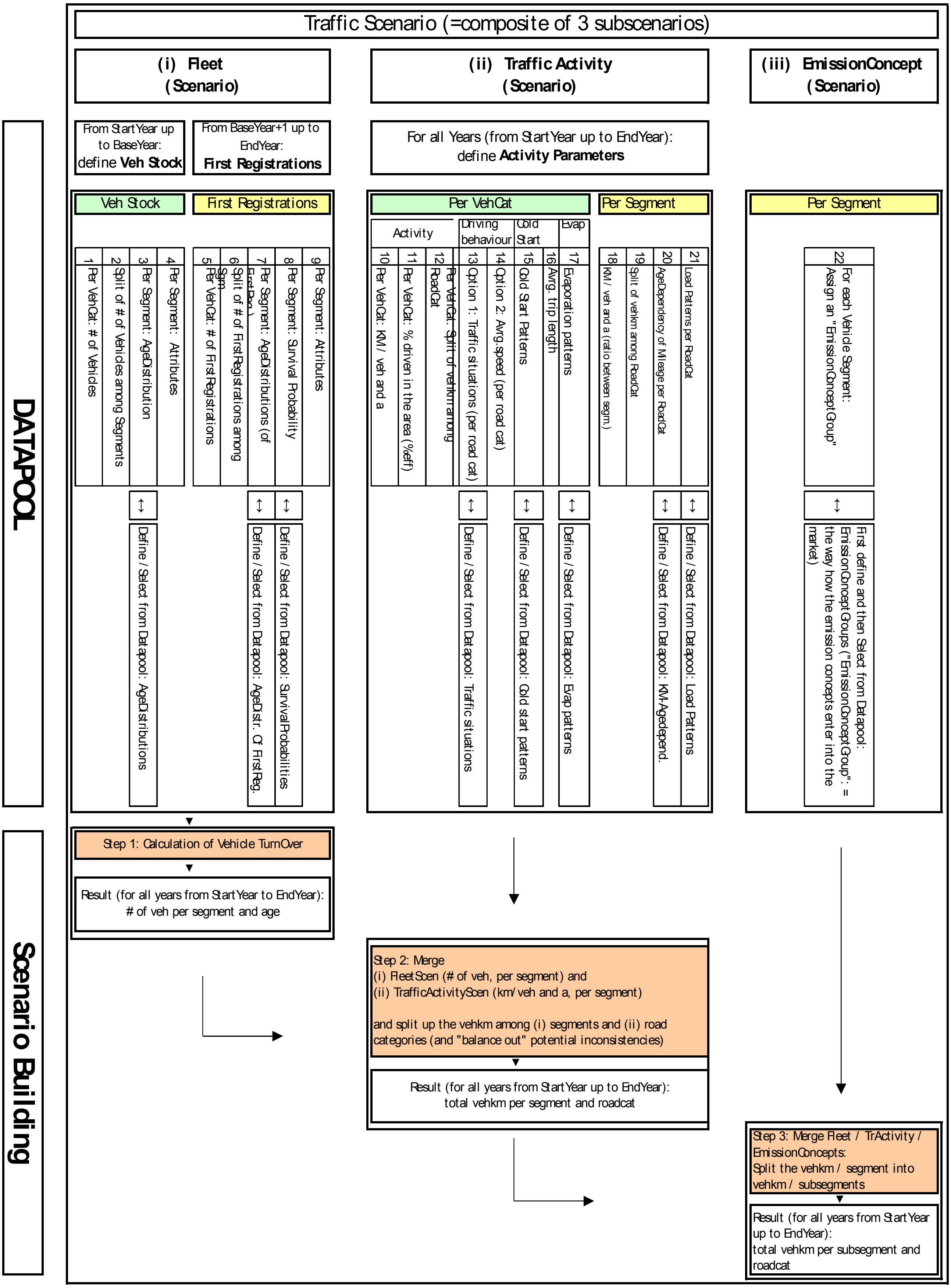


Figure G-3: Overview of the ARTEMIS fleet model (Keller and Kljun, 2007a).

Sub-scenario 1: fleet scenario

For the **past**, the model requires statistics relating to the number of vehicles and age distributions. The model works at the 'segment' level. In other words, for each reference year, the user must specify

- The total number of vehicles per vehicle category.
- The split between segments (by year and vehicle category).
- The corresponding age distribution for each segment.

For the **future**, the module calculates the fleet turnover ('step 1' of the fleet model), whilst the inputs are defined in the data pool. The model offers two possibilities for this:

- Option A1 is based on assumptions about future new registrations and survival rates. More specifically, the input is:
  - The total number of new registrations in a particular future year (per vehicle category).
  - The split between segments in that year (per vehicle category).
  - The corresponding survival rate for each segment.

  In this manner, the model knows the 'inflow' to the fleet and - by the survival rates – how many of the vehicles of year X-1 will still be in the market in the year X. Some of the 'new' vehicles may actually be used cars (*e.g.* from abroad). Therefore, the new registrations have to be specified with a particular 'age distribution of new registrations'.
- Option A2 is based on assumptions about the total vehicle stock in future years. In this case, the following inputs have to be specified:
  - The total number of vehicles in a particular future year (per vehicle category).
  - The split between segments in that year (per vehicle category).
  - The corresponding survival rate for each segment.

  In this case, the model knows – by the survival rates – how many of the vehicles of year X-1 will still be on the road in year X. Since the total number of vehicles for year X is also given, the model calculates the difference as being the 'inflow'. Inconsistencies may arise (*e.g.* if the difference is negative, which means that the survival rates overestimates the total number of vehicles on the road). In such cases the model provides an option to recalculate the fleet.

Emission levels depend on particular attributes of the vehicles, including the use of air conditioning and exhaust after-treatment systems such as particulate filters. The user has to specify the shares of vehicles with such attributes. These attributes have to be specified at the segment level, and along the same lines as the basic information on the vehicle fleet for the past and the future. However, for the description of the past, there is an interaction between the age distribution of all vehicles in a particular segment and the age distribution of those with a given attribute (*e.g.* air conditioning), and inconsistencies may arise. Further details of this should be checked, and are outlined in the User Guide (Keller and Kljun, 2007b).

Sub-scenario 2: traffic activity scenario

The traffic activity scenario defines basically the mileage (km/vehicle), but adds different inputs which differentiate this mileage (*e.g.* by adding functions which take into account the age dependency of the mileage).

The following inputs are required:

- The km/year of the average vehicle per category and per year. In addition, the user can specify whether this mileage is driven entirely in the area of the study. For smaller countries a certain percentage may be driven outside the country, and in this case a second fleet composition might have to be considered.
- The relative split of the mileage between the three road categories (motorway, rural, urban) per year.
- For HGVs only, a 'transformation pattern'. In general, registration data refer to 'trucks' – ignoring whether trucks are rigid or articulated, which makes a difference in terms of the emissions. Hence, a transformation pattern determines how the average mileage specified above has to be split between rigid and articulated vehicles.

Since different vehicles segments tend to have a different mileage or other characteristics, other inputs have to be specified.

<u>Relative mileage between segments.</u> This allows the user to specify whether, for example, larger vehicles have a higher mileage than smaller ones. This input is adjusted in the modelling process in order to retain (as a weighted average) the mileage defined at the vehicle category level.

Split of the mileage between the road categories per segment. The mileage input takes place on two levels:

- At the vehicle category level (km/vehicle and year, and split between road categories).
- At the segment level (relative km/vehicle and year, and split between road categories per segment).

This may create inconsistencies. The model therefore provides a balancing procedure to guarantee consistency. The mileage information for the vehicle category level is taken as being the more reliable. In addition, the balancing procedure requires not only the mileage information, but also data about the fleet and its split between the segments, since this determines the weights to be used. Therefore, this balancing procedure is part of the scenario building process.

Age dependency of the mileage. It is known that newer vehicles tend to have higher annual mileages than older ones. This information can be specified per road category. If no detailed information is available, the same function may be used for all road categories. The model calibrates the mileages in such a way that the resulting absolute average mileage will correspond to the value specified in the section 'per vehicle category'. This also requires information on the fleet, and hence is calculated during the fleet modelling process.

Load factors. Load factors are only required for HGVs. Three load categories are used for each vehicle segment: full (100% loaded), 50% loaded and empty (0%) loaded. In addition, this information can be specified as a function of the age of a segment (if available).

Sub-scenario 3: emission concept scenario

This part of the model defines an 'introduction scheme' for each vehicle segment which determines when the different technologies and concepts enter the market (*i.e.* this links construction years of the vehicles to the emission concepts). This introduction can be defined gradually (*i.e.* in a particular year several different emission concepts can be present at the same time, since in general the concepts are not introduced entirely from one year to the following year).

Production of traffic scenarios

A traffic scenario is a composite of the three sub-scenarios mentioned above, and has to be constructed in three steps:

- Step 1: the fleet scenario calculates the turnover of fleet from the start year up to the end year.
- Step 2: the fleet data (vehicle stock) and traffic activity data (km/veh and year) are combined to give the total mileage for the fleet (veh/km for the study area). Here, the balancing procedure has to be applied in order to guarantee consistency.
- Step 3: the information relating to the introduction of emission concepts over time is added. This step produces the vehicle-kilometres (mileage) as well as the vehicle stock information for the study area.

Access to the fleet model results

The fleet model results can be accessed in several ways in the fleet model:

- There are additional options which allow access in graphical and tabular form:
  - Total vehicles and vehicle-km by sub segment (total or by road category).
  - Total vehicles and vehicle-km by segment (total or by road category).
  - Total vehicles and vehicle-km by emission concept (total or by road category).
- There are several possibilities for evaluating time series (*e.g.* vehicle-km, vehicle-km/segment, vehicle-km/sub segment). This allows the user to check the plausibility and completeness of the results.

Simplified fleet composition

The model also provides a simplified form to define the fleet composition directly, without going through the (time consuming) steps of the fleet model. This dataset corresponds to the output of the fleet model. However, the fleet model differentiates between the three road categories; with the simplified approach the same fleet composition is used for all road categories.

G2.3 Calculation tools

This Section provides a brief overview about the tools which are available in the model for working with emission factors and traffic activity data. More details are given in the User Guide (Keller and Kljun, 2007b).

'Emission Factors' menu

The Emission Factors menu allows the user to access various emission factors, in a manner which is similar to the DACH-Handbook Emission Factors (**Figure G-4**).

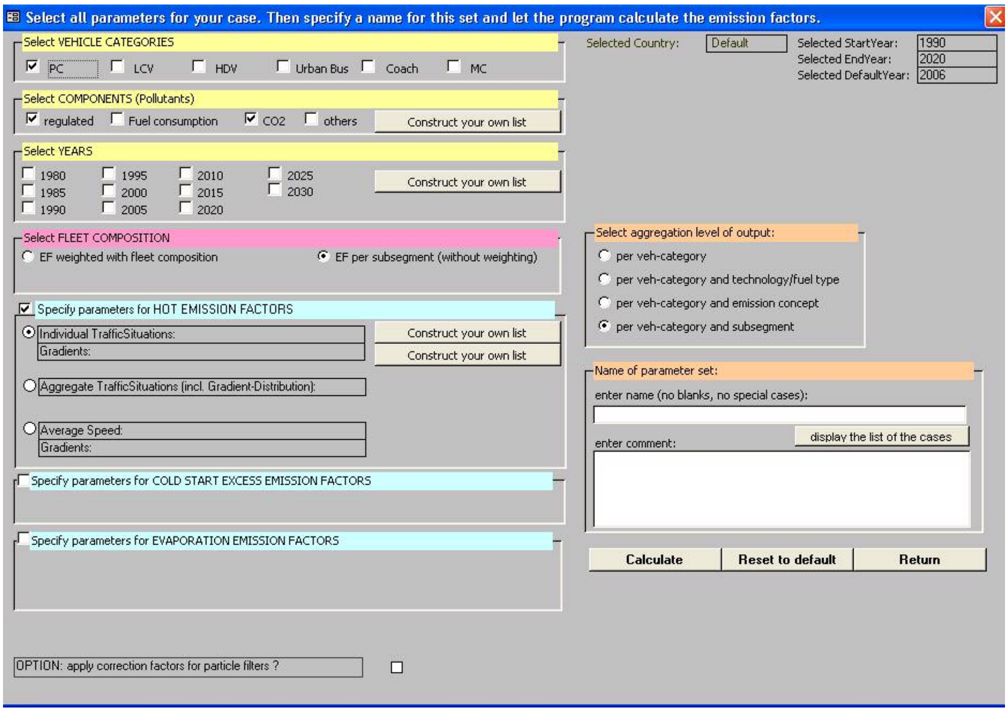


Figure G-4: Emission Factors menu (Keller and Kljun, 2007a).

The user can specify what is required from the model in terms of, for example:

- The **vehicle categories**.
- A list of **pollutants**.
- The **years** of interest: this requires that the user has specified a fleet composition for the particular years.
- A (user-specified) **fleet composition. T**his refers to the traffic scenario specified in the fleet model, and allows the user to calculate weighted emission factors (*e.g.* for a fleet in country X for year Y). Alternatively, the user can request 'unweighted' emission factors, and the model provides emission factors per vehicle sub segment.
- The **hot emission factors,** for which three types are available:
  - Individual traffic situations for different gradient classes.
  - Aggregate traffic situations. This requires that the user has specified 'aggregate (traffic situation) TS-gradient-patterns'.
  - Average speed emission factors (in 5 km/h bands) for different gradient classes.
- **Cold start emission factors,** by selecting a 'pattern of ambient conditions'.
- **Evaporative emission factors**, by selecting the type (diurnal, soak, running losses) and again a 'pattern of ambient conditions'.
- **Option PF** (diesel particulate filters). This option takes into consideration that some vehicles are equipped with particulate filters.
- **Specification of the output**. The user then has to specify the level aggregation of the output desired - *i.e.* whether the emission factors should be provided per vehicle category, per technology/fuel type, per emission concept or – at the most detailed level – per sub segment. In addition, the results are saved under a user-specified file name.

Additional options allow the user to export the results, to delete any files created, to rename files, *etc*. The results are stored in the 'User Database' (a MicroSoft Access database).

'Traffic Data Sets' menu

The emission model requires the specification of the traffic activity in a particular format in order to calculate emissions for the different types of source (hot, cold start, evaporation). This format is called the 'traffic data set', and is represented as four tables – one for hot emissions (vehicle-km), one for cold start emissions (number of starts), one for hot soak evaporative emissions (number of stops), and one for diurnal evaporative emissions (number of vehicles).

The model allows application at the aggregate level (*e.g.* a country or a region) and on a road link level (for networks). Each level has its own definitions, and hence a traffic data set contains 8 (2x4) tables.

The Traffic Data Sets menu allows the user:

- To specify the basic definitions for both aggregate and link-based applications.
- To edit the different tables.
- To analyse the traffic data sets.
- To create, rename or delete data files.

In addition, a special tool allows the user to transform the traffic activities specified in the fleet model into the appropriate form for use as a traffic data set for emission calculations. Again, the traffic data sets are stored in the User Database.

Emission Model menu

The Emission Model menu allows the user to calculate the emissions for a specific case, provided that the user has specified the input – particularly the description of the traffic activity in the form of a traffic data set. The Calculate Emissions menu can then be used to perform the calculations according to the user's specification. A certain set of inputs is defined by the traffic data set (vehicle categories, years, traffic situations or average speed, patterns of ambient conditions). In addition, the user has to specify the pollutants of interest, the types of emission source to be included and the format of the output (level of aggregation, name of the result file).

The model also provides tools to enable the user to analyse the result by a large number of predefined queries. The results are again stored in the User Database.

G2.4 Application of the ARTEMIS road model in Sweden

Introduction

The first implementation of the ARTEMIS road model took place in Sweden, and for this a joint research project was initiated at the end of 2004. The organisations involved in the project were IVL, AVL MTC, VTI and LTH at Lund University (Sjödin *et al.*, 2006).

Prior to 2003, Sweden had used a national road transport emission model for reporting atmospheric emissions to the UNFCCC (the Kyoto protocol), the EU NEC Directive, and the UNECE Convention on Long-Range Transboundary Air Pollution (CLRTAP). However, a strategic decision was taken by the Swedish Road Administration (SRA) to switch to a common EU model, with the first choice being ARTEMIS. The aim of the project was therefore to implement and evaluate the new ARTEMIS road model in Sweden. Since, according to the Kyoto protocol, no changes in methods are allowed in the reporting to UNFCCC after 2005 for the first commitment period, the implementation of the ARTEMIS model in Sweden, at least for the direct greenhouse gases CO_2, N_2O and CH_4, needed to be completed before the end of 2005 and to cover the whole time series 1990-2004.

The results presented by Sjödin *et al.* (2006) were obtained using version 0.2T of the model, and the work is described below.

Model application

<u>Sources of fleet data</u>

The Swedish vehicle fleet is described in terms of numbers of vehicles by category, segment and age in the National Vehicle Register. The Register is updated with new registrations and scrapped vehicles on a daily basis. In this work, the data which were available by 31 December of each year were used.

For vehicle segment and age distribution, some of the definitions used in the ARTEMIS model are not used in the National Vehicle Register. For instance, for passenger cars no information on engine capacity was available in the Register. Information on the engine capacity of different car models sold in Sweden was, however, available from the Swedish Consumer Agency. Based on a combined dataset, separate engine capacity functions were derived for diesel and petrol cars, in which engine capacity was expressed as a function of year of registration, engine power and vehicle weight. The distinction between coaches and urban buses was based on the quotient '***p*/*w***', where ***p*** is the maximum allowed number of passengers and ***w*** is the gross vehicle weight. An urban bus was defined as a vehicle with a ***p*/*w*** quotient of more than 3.75, and all other vehicles were assumed to be coaches. Two vehicle segments were used for trucks: 'with trailer' and 'without trailer'. In the National Vehicle Register there was no information on the use of trailers. Trucks with trailers were therefore described using vehicle transformation patterns which described the distribution of mileage in each weight class for vehicles with and without a trailer. The 'with trailer' segment was further divided into different sizes of trailer, expressed in terms of the total weight for the vehicle-trailer combination. For motorcycles, information on engine capacity was available from the National Vehicle Register. However, the type of engine (2-stroke or 4-stroke) was not given. The engine type was therefore estimated based on year of registration, engine capacity, engine power and manufacturer.

For each segment in a given category an age distribution was defined, and this covered a 60-year period. The definition of the age of a vehicle was based on the first date of registration according to the National Vehicle Register. For privately imported cars, the year of first registration was replaced by the year of manufacture. For each vehicle segment, each year of first registration was assigned to one or more emission concept groups by means of the function 'Introduction schemes of emission concepts' in the ARTEMIS model. The code representing a vehicle's emission concept group in the National Vehicle Register was occasionally missing. In such cases, codes were assigned based on the year of first registration together with the dates of the introduction of new exhaust regulations.

Sources of activity data

The ARTEMIS model requires annual mileages by vehicle category. These were calculated using a national road mileage model. The inputs to this model were mileage on the roads administrated by the SRA, based on traffic measurements, along with the numbers of vehicles in different categories. Statistics Sweden has developed a method which can be used to assign an annual mileage to all vehicles in the Register, based on yearly odometer readings within the Swedish in-service inspection and maintenance programme. These data were used for deriving both the sub segment level mileage, and for estimating mileage as a function of vehicle age.

Load patterns as a function of age were used for heavy commercial vehicles by segment. For each segment the ARTEMIS model requires a mileage distribution of load factor 0% and 1-99% for the 60 year classes. These data were estimated based on a major national survey ('Swedish domestic road goods transport') from 1997, which included detailed information on both truck and trailer loads.

In order to estimate evaporative and cold-start emissions, data on trip lengths, parking times and seasonal and diurnal variation in ambient temperature were derived using instrumented cars (giving the distance from engine start to engine stop). For Sweden, an average trip length of 7 km was used.

The function 'fuel quality' in the ARTEMIS model was used to correct emissions from diesel engines, and to estimate evaporative emissions and SO_2 based on fuel composition. Prior to 1990 the Swedish Environmental Protection Agency analysed samples from filling stations. For 2000 onwards, data were available from the Swedish Petroleum Institute. In the ARTEMIS model, diesel fuel qualities are described in terms of 'pre-Euro I' to 'Euro IV'. However, by mainly using the sulphur content for classification the deviation, at least for SO_2, should be minor.

Relating Swedish traffic data to the ARTEMIS traffic situations

The ARTEMIS model includes 276 traffic situations (TSs). These are based on a combination of road type, speed limit and traffic flow condition (**Table G-1**). The Swedish road categories were translated into ARTEMIS traffic situations based on the description of the road hierarchy, the speed limit, and the road function and design (Larsson and Ericsson, 2006). It is also possible to introduce different levels of gradient in ARTEMIS, although this was not done for Sweden. The calculations were performed for the years 1990, 1995, 1998, 2000 and 2004.

Firstly, a database was required in which each road was associated with information on: (i) the traffic flow and road length, to compute the vehicle mileage, (ii) the road function and (iii) the speed limit. In Sweden, roads are owned and maintained by the state, by municipalities, or privately. For the state roads there is a complete and accurate GIS road database called VDB. This database is updated annually by the SRA, and ccontains all state road links, together with information on length, function, speed limit, average daily traffic flow, and the proportions of light-duty and heavy-duty vehicles. For municipal and private roads there is a complete digital map called the National Road Database (NVDB), in which road function and speed limit are included, but the traffic flow is not given.

On the basis of the vehicle mileage for the state road network, the SRA estimates the total vehicle mileage in Sweden using the Vehicle Mileage model (VM model). This model contains total mileage for each year since 1990, and is produced by The Swedish Institute for Transport and Communications Analysis (SIKA) and the Swedish National Road and Transport Research Institute (VTI) (SIKA and VTI, 2005). To estimate the traffic flows on the municipal and private roads, the traffic demand model SAMPERS and the traffic model EMME/2 were used for four test regions. These regions were chosen to represent the distribution over road types for municipal and private roads for the whole of Sweden. Traffic was simulated on a detailed and classified road network according to the NVDB. To differentiate the vehicle mileage on urban and rural roads, polygons defining built-up areas were used. The following definition of a built-up area was used: ‘a group of buildings normally not more than 200 metres apart, and a minimum of 200 inhabitants’ (SCB, 2005).

Table G-1: Principle for division into traffic situations (Keller *et al*., 2005; Andre *et al*., 2006).

Area	Road type	Speed limit (km/h)	Traffic flow conditions
Urban	Motorway - national (through traffic)	80, 90, 100, 110, 120, 130	4 levels of service
	Motorway - city	60, 70, 80, 90, 100, 110	4 levels of service
	Main trunk road - national	70, 80, 90, 100, 110	4 levels of service
	Trunk road - city	50, 60, 70, 80, 90	4 levels of service
	Distributor-district connection	50, 60, 70, 80	4 levels of service
	Local collector	50, 60	4 levels of service
	Access - residential	30, 40, 50	4 levels of service
Rural	Motorway	80, 90, 100, 110, 120, 130, >130	4 levels of service
	Semi motorway (2+1 lanes, variable)	90, 110	4 levels of service
	Trunk road	60, 70, 80, 90, 100, 110	4 levels of service
	Distributor - district connection	50, 60, 70, 80, 90, 100	4 levels of service
	Distributor - district connection (with curves)	50, 60, 70, 80, 90, 100	4 levels of service
	Local collector	50, 60, 70, 80	4 levels of service
	Local collector (with curves)	50, 60, 70, 80	4 levels of service
	Access-residential	30, 40, 50	4 levels of service

Distribution of national vehicle mileage

The correspondence between vehicle mileage and the ARTEMIS TSs was based on a top-down model (**Figure G-5**). The total vehicle mileage was separated into the three road administration categories using the VM model. The proportion of vehicle mileage on urban and rural roads was calculated for each road administration category. The urban vehicle mileage was then divided into three classes based on the number of inhabitants. The last step before matching the Swedish road categories with an ARTEMIS traffic TS was to adjust the relationship between the average daily traffic flow and the traffic volumes in ARTEMIS’s four classes for traffic conditions (levels of service), using the speed-flow curve for different types of road.

For the state, municipal and private road networks, information on the distribution of vehicle mileage for the years considered was obtained from SIKA and VTI, and was converted using the VM model. The vehicle mileage on state roads in the VM model is based on 80 measurement points (Björketun *et al*., 2005). The total vehicle mileage was found to increase from 64,310 to 74,599 million km between the years 1990 and 2004. The proportion on state roads increased from 66% to 68%, and there was a corresponding decrease on municipal roads (30% to 28%). Private roads were estimated to have a constant share of 4% of the total vehicle mileage. Due to the completeness of the information in the VDB, it was possible to recalculate the total vehicle mileage for state roads. The average daily traffic flows in VDB are based on the numbers of vehicles or ‘pairs of axles’ during a specific year. To calculate the total vehicle mileage for a certain year, the flow value was scaled using an index which showed how the traffic flow has increased or decreased since the year it was measured (Johansson *et al.*, 2002; Holmgren, 2004). Once all links had been scaled for the intended years, the total vehicle mileage on state roads could be calculated using a bottom-up approach, and compared with the top-down values in the VM model. There was a small difference between the two methods, but in this study the scaling method was used for all distributions.

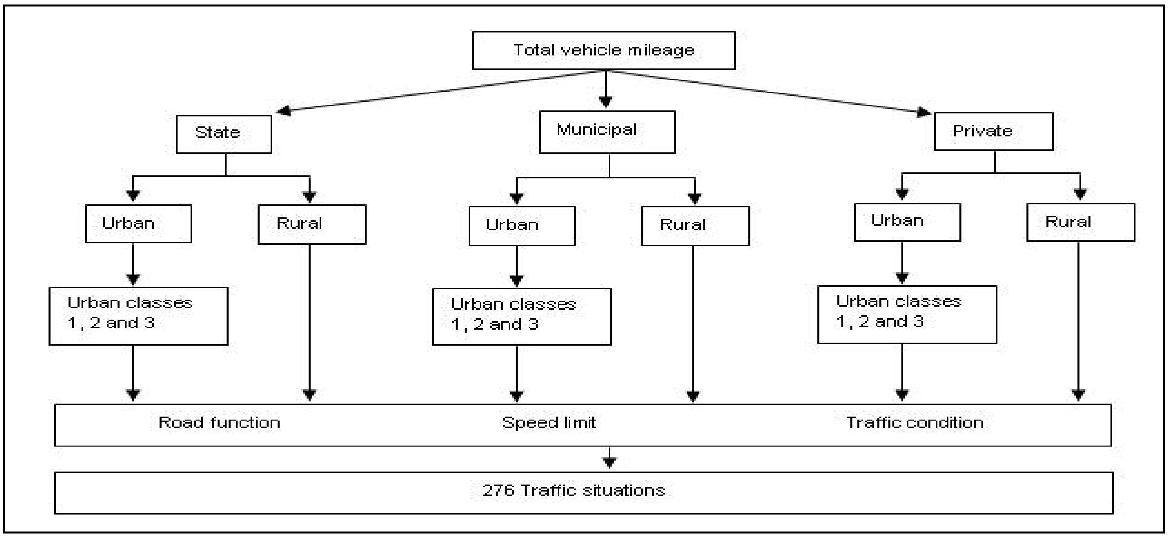


Figure G-5: An overview of the distribution of vehicle mileages in the top-down model.

Vehicle mileage was also allocated to urban and rural roads (which were defined using the polygon method mentioned earlier for all years). The results showed an increase in vehicle mileage on state rural roads from 78% to 82% between 1990 and 2004. Due to the lack of traffic flow data for the municipal and private road network, four test regions with simulated traffic data were used to distribute mileage between urban and rural areas. The four regions studied were three counties (Stockholm, Uppsala and Östergötland) and one municipality (Halmstad). The same overlay method was used for these areas as for the state road network. For the municipal road network the results showed that 89% of the vehicle mileage was driven on urban roads. The corresponding proportion on the private road network was 25%. The total distributions on urban and rural roads for the different road administration categories are given in **Table G-2**.

Table G-2: The distribution of vehicle mileage for urban and rural roads in Sweden during 2004.

	Urban	Rural	Total
State roads	15 %	53 %	68 %
Municipal roads	25 %	3 %	28 %
Private roads	1 %	3 %	4 %
Total	41 %	59%	100 %

Urban vehicle mileage, as well as the distribution over road types and traffic conditions, is likely to be related to the size of the city. The next step in the distribution model was therefore to find a method of calculating the vehicle mileage for cities with different populations. One hypothesis is that the number of TSs, as well as the proportion of vehicle mileage per TS, varies depending on the city size (population). Due to the fact that national data for the municipal and private road network were incomplete, the polygons describing the built-up areas in the four test regions were used. The 207 areas were classified into three groups based on the number of inhabitants: (i) villages and small towns (200-49,999 inhabitants), (ii) towns and small cities (50,000-199,999) and (iii) large cities (≥200,000) in accordance with classifications made by Vilhelmson (2000).

An equation for the vehicle mileage within a city as a function of the number of inhabitants was obtained through regression analysis:

Vehicle mileage = 3975.81 * Number of inhabitants (Equation G-1)

The R^2 value for the equation was 0.997 including Stockholm, and 0.95 excluding Stockholm. Equation 1 was applied to distribute the urban traffic over different kinds of built-up area (**Table G-3**).

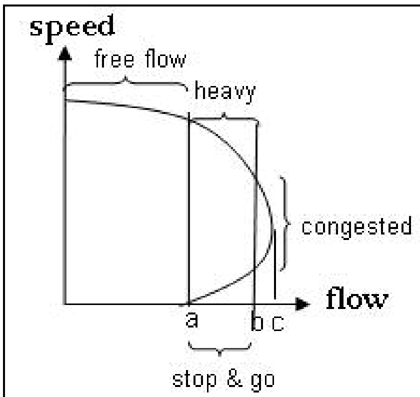
Table G-3: The vehicle mileage in 2004, distributed over the three types of built-up areas.

Type of built-up area	State roads	Municipal and private roads
Villages and small towns (200 – 49 999 inh.)	58.9%	58.1%
Towns and small cities (50 000 – 199 999 inh.)	12.5%	16.5%
Large cities (> 200 000 inh.)	28.6%	25.4%
Total	100%	100%

Functionality, speed limit and traffic conditions

The ARTEMIS model defines 69 road types (when both functionality and speed limit are included) (**Table G-1**). Each road type is further divided into four classes of traffic condition, termed 'levels of service', giving a total of 276 traffic situations. The prevalence of road categories, as well as their shares of total vehicle mileage, varies between countries, and conditions in Sweden had to be matched to those in ARTEMIS. The classifications in the two Swedish road databases (VDB and NVDB) were therefore translated into the classifications used in ARTEMIS. The translation was based on the road hierarchy (national, primary, secondary, *etc.*), the road function and design (motorway, dual carriageways, single-lane roads, *etc.*), and the prevailing speed limit. In total, 33 of the ARTEMIS road types were identified in Sweden.

To distribute the vehicle mileage on different roads over different traffic conditions, ranking curves for the yearly distribution of traffic flow were applied. These were based on measurements of the distribution of traffic flow over the hours of a year for different road types (Björketun *et al.* 2005, Jensen 1997), and were sub-divided between light- and heavy-duty vehicles. Calculations of traffic flow and vehicle mileage at different hours (using ranking curves) for different links were performed for all state road links. These calculations were also performed for the municipal and private road links in the test regions of the county of Östergötland, the municipality of Halmstad and the Stockholm area (for which new traffic simulations were performed to represent traffic flow in large cities). Urban and rural roads have different ranking curves, and thus separate procedures were used. The result - traffic flow per lane and per hour for different ranked classes - was related to volume-delay functions according to **Figure G-6**, and initially classified into levels of service 1-3.



Road speed limit	Capacity (c in figure veh./lane*h)	Condition 1 "Free flow" (a in figure)	Condition 2 "Heavy" (a-b)	Condition 3 "Congested" (b in figure)
90+	2000	<1300	1300-1700	≥ 1700
70	1550	<600	600-1300	≥ 1300
50-	1150	<600	600-900	≥ 900

Figure G-6: Principles for classifying different flows (vehicles/lane*hour) on roads links with different speed limits as ARTEMIS traffic conditions 1-3. Limits for different traffic conditions were extracted from TU71 volume delay functions (Matstoms, 2004).

For level of service 4 ('stop-and-go'), a different approach was applied . It was not possible from traffic flow data alone to determine between 'free-flow', 'heavy' and 'congested' in **Figure G-6**. Thus, it was not possible to quantify the vehicle mileage under stop-and-go conditions. To overcome this, two assumptions were made. Firstly, it was assumed that stop-and-go conditions would only occur on road links that had reached their capacity. Secondly, for these roads it was assumed that stop-and-go constituted a fixed share of the vehicle mileage which was initially estimated to be in the 'heavy' traffic condition. By studying flows over the day for individual congested roads (**Figure G-7**), it was seen that a local decrease in flow sometimes occurred within a congested period (*i.e.* when flow was near the capacity). This period was assumed to be a stop-and-go period. Thus, for links reaching their capacity the vehicle mileage under 'stop-and-go' conditions was estimated to be 14% of the vehicle mileage that had initially been assigned to 'heavy'. The vehicle mileage under heavy conditions was decreased correspondingly. Vehicle mileage was finally summed over all road classes and traffic conditions, and the translated into the ARTEMIS TSs.

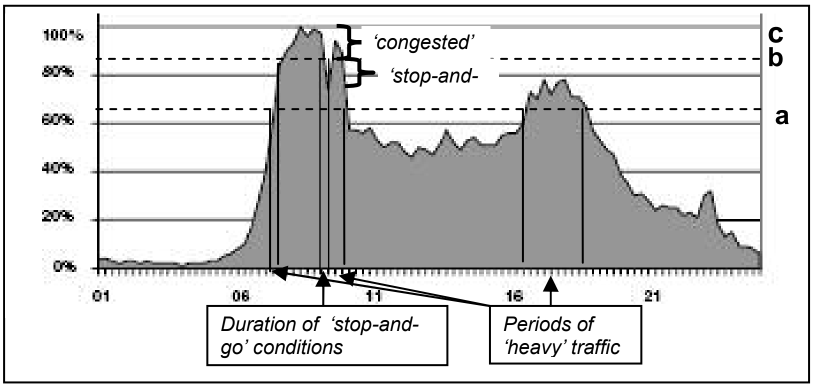


Figure G-7: Principle for quantification of stop-and-go conditions on congested roads. For definitions of a, b and c see **Figure G-6.**

Traffic situations in Sweden in 2004

In terms of the different road administration categories, the largest share of vehicle mileage (53%), was driven on state roads in rural areas. The second largest share (26%), was driven on municipal roads in urban areas, and the third on state roads in urban areas (14%) (**Figure G-8**). In total 59.2% of vehicle mileage was driven in rural areas (of which 14.6% on motorways and 44.5% not on motorways) and 40.8% in urban areas (of which 4.0% was on motorways and 36.9% not on motorways). Before this study the rural share of vehicle mileage in Sweden had been assumed to be 65% (Ringhagen, 1987).

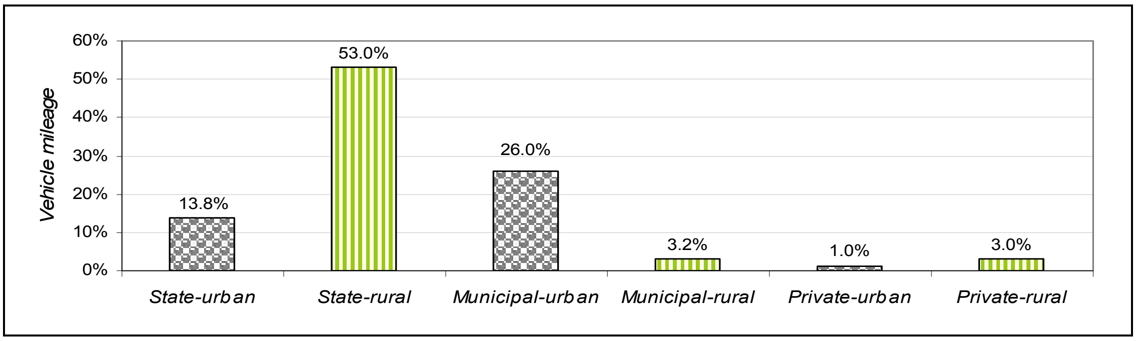


Figure G-8: Distribution of vehicle mileage in Sweden on urban and rural roads for different road administrations, for the year 2004.

The result of the distribution of the total vehicle mileage over the road types and traffic conditions on urban and rural roads in Sweden showed that 85 of the 276 ARTEMIS TSs were found in Sweden in 2004. Of these 85, 45 were in rural areas and 40 in urban areas. The TSs covered 33 road types, and most of them never exceeded the traffic conditions 'free-flow' (level of service 1) and 'heavy' (level of service 2). In fact, as much as 94% of the vehicle mileage in Sweden is driven under free- flow conditions, 3.4% in heavy traffic, 2.1% in congested traffic, and as little as 0.05% under stop-and-go conditions. Stop-and-go traffic occurred only in the largest cities. The ten most common TSs in Sweden are presented in **Table G-4**.

Table G-4: The ten most common TSs in Sweden in 2004, and their share of the total vehicle mileage.

Description of traffic situation	Vehicle mileage
Rural/distributor-district connection, speed limit 90 km/h, free-flow	21.3%
Rural/distributor-district connection, speed limit 70 km/h, free-flow	11.1%
Rural/motorway, speed limit 110 km/h, free-flow	10.7%
Urban/local collector, speed limit: 50 km/h, free-flow	9.7%
Urban/access-residential, speed limit 50 km/h, free-flow	6.6%
Urban/distributor-district connection, speed limit 70 km/h, free-flow	5.9%
Rural/local collector, speed limit 70 km/h, free-flow	5.7%
Urban/distributor-district connection, speed limit 50 km/h, free-flow	4.8%
Urban/access-residential, speed limit 30 km/h, free-flow	2.2%
Rural/trunk road, speed limit 110 km/h, free-flow	2.0%
Total	79.9%

Comparisons with other approaches

Comparisons with the national EMV model

The nationally developed road vehicle emission model EMV has been used since the mid 1990s for Sweden's international reporting obligations on air emissions (Hammarström and Henriksson, 1997; Hammarström and Karlsson, 1998). The EMV model is considered to be a top-down model, which calculates emissions of regulated and some unregulated compounds for different vehicle categories, mainly according to two traffic situations - urban and rural driving. Besides hot emissions, the EMV model calculates cold-start and evaporative emissions taking into account Swedish climate, the vehicle fleet, *etc*. For light-duty vehicles, the hot and cold-start emission factors are taken from measurements over the US FTP driving cycle. Cold-start emissions from US FTP are adjusted for Swedish conditions. For heavy-duty vehicles, the emission data are mainly from the same sources that used in the ARTEMIS model (*i.e.* COST 346), and are for the Swedish fleet and road conditions. Thus, the main differences between the two models are the number of traffic situations available, and the driving cycles representing emissions for light-duty vehicles. The EMV model calculates emissions down to a level formed by the combination of vehicle type, engine type, model year, emission concept, and fuel quality. For the present project the activity data in the EMV model were updated to be as equivalent as possible to the activity data required for the ARTEMIS model.

Compared with the EMV model, the ARTEMIS model gave 3% higher CO_2 emissions in 1990 and 6% higher emissions in 2004 (**Figure G-9**). The observed differences were mainly due to higher fuel consumption for HDVs in the ARTEMIS model, especially for pre-1990 vehicles, and higher fuel consumption for new passenger cars in ARTEMIS. The decrease in fuel consumption over the years is also smaller in the ARTEMIS model than in the EMV model. The fuel consumption for cars with an engine capacity larger than 2 litres is actually increasing over the years according to the ARTEMIS model, most likely because the average engine size within this vehicle segment is increasing.

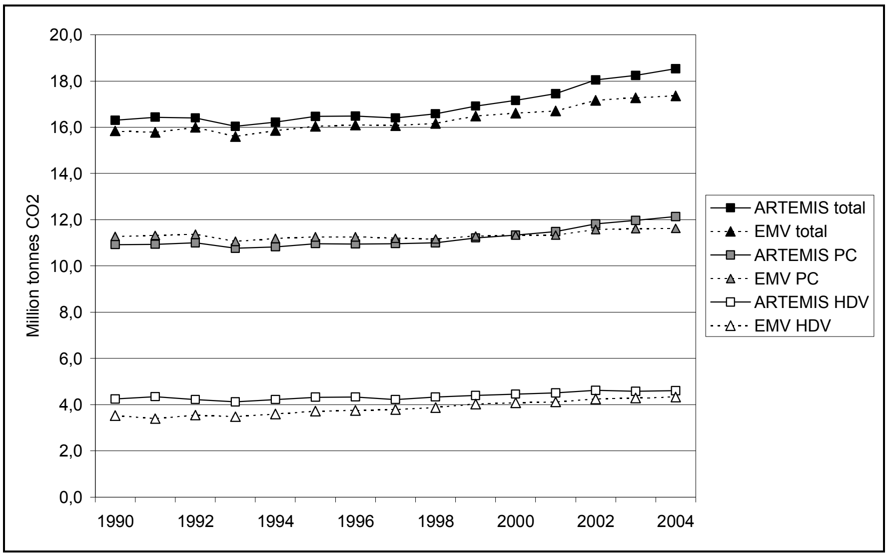


Figure G-9: Yearly national CO_2 emissions from road traffic in Sweden for the period 1990-2004 according to the ARTEMIS model and the national model (EMV), respectively.

For NO_x, the ARTEMIS model gave 4% higher emissions in 1990 and 19% higher emissions in 2004 compared with the EMV model (**Figure G-10**). The main reason for this was that the ARTEMIS model generally predicts higher emissions for gasoline passenger cars.

For HC, the ARTEMIS model gave markedly higher emissions than the EMV model, in both 1990 and 2004: 59% and 42% respectively. Comparisons between the two models for gasoline PC HC emissions, separated into hot, cold-start and evaporative emissions, are shown for 1995 and 2005 (**Figure G-11**). It can be seen that, whereas cold-start emissions are similar between the two models, the ARTEMIS model yields substantially lower hot emissions and much higher evaporative emissions. The uncertainty of, in particular, the evaporative emissions is considered to be high, since both models are based upon very limited numbers of measurements.

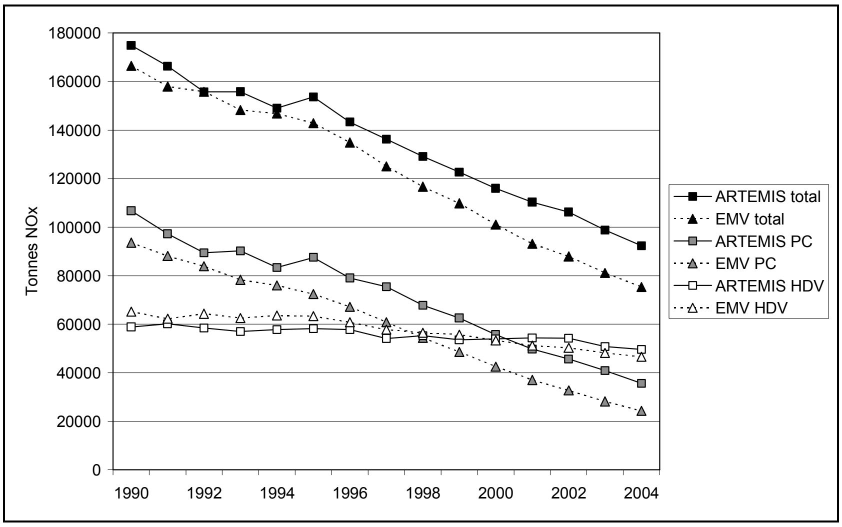


Figure G-10: Yearly national NO_X emissions from road traffic in Sweden for the period 1990-2004 according to the ARTEMIS model and the national model (EMV), respectively.

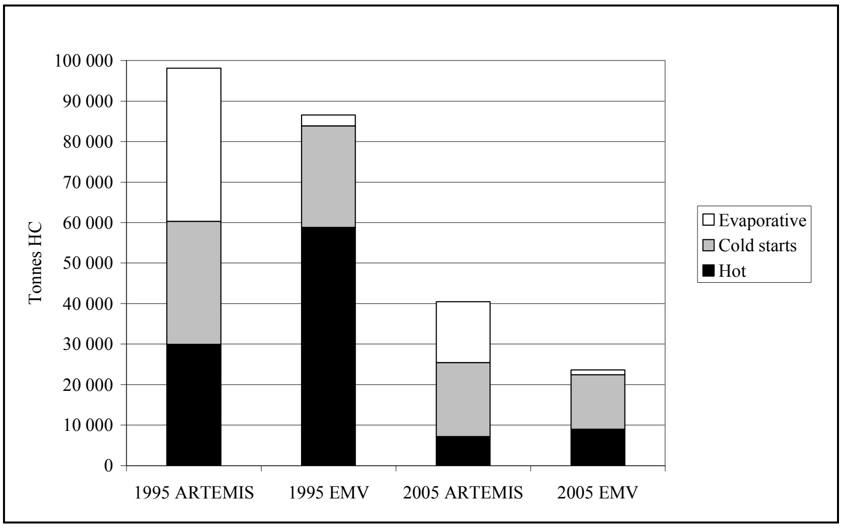


Figure G-11: HC emissions from gasoline passenger cars in Sweden in 1995 and 2005 according to the ARTEMIS road model and the national model (EMV), respectively.

<u>Comparisons with on-road emission data</u>

On-road emission data were taken from a major remote sensing measurement campaign carried out in Göteborg in 2001 and 2002. The campaign was originally used to evaluate the COPERT III model (Ekström *et al.*, 2004). The dataset comprised of instantaneous emissions of CO, HC and NO (expressed as grammes of pollutant released per litre fuel burnt) for 18,000 gasoline passenger cars, 1,000 diesel passenger cars, and 600 heavy commercial vehicles. The two measurement sites were classified according to the ARTEMIS traffic situation scheme as 'Urban Distributor with speed limit 50 km/h and slight uphill gradient (about 2%)'. In fact, one of the sites actually had a posted speed limit of 70 km/h, but the actual measured average speed was closer to 50 km/h.

The results are presented in **Figures G-12** and **G13**. For hot emissions from gasoline passenger car there was, in general, a good agreement between modelled and on-road data for all three pollutants covered (CO, HC and NO). The results for CO and NO showed similar patterns as those shown for HC. This provides strong support for both this aspect of the ARTEMIS (gasoline passenger cars, hot regulated emissions), not only for present conditions but also for the past (*e.g.* 1990), as well as for on-road optical remote sensing being a powerful tool for verifying and evaluating road vehicle emission models. As can be seen in **Figure G-13**, there was also a fairly good agreement between the ARTEMIS model and on-road data for HDV NO_x emissions, although the on-road data did not reveal any significant differences in NO_x emissions between the Euro I, II and III classes.

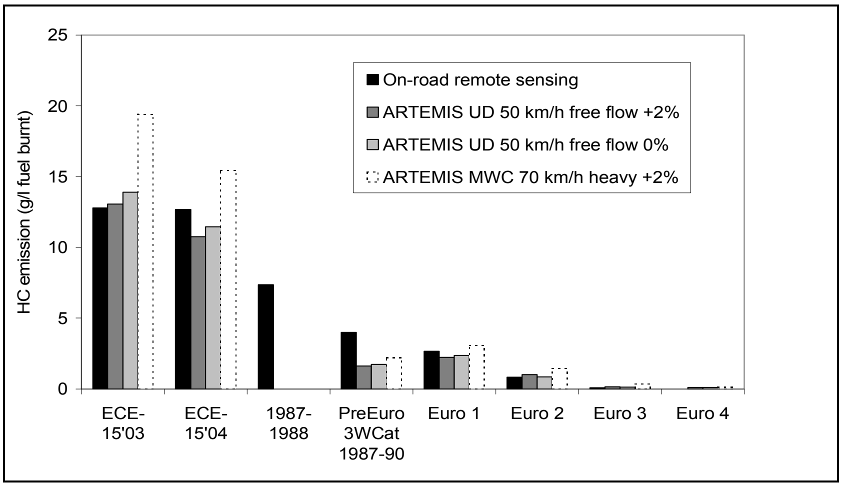


Figure G-12: Emission factors for HC for gasoline passenger cars from remote sensing measurements and the ARTEMIS model (UD = Urban Distributor, MWC = Motorway City, 50/70 km/h = posted speed, free flow/heavy = level of service, %-figures = applied road grade according to ARTEMIS road model traffic situations definitions).

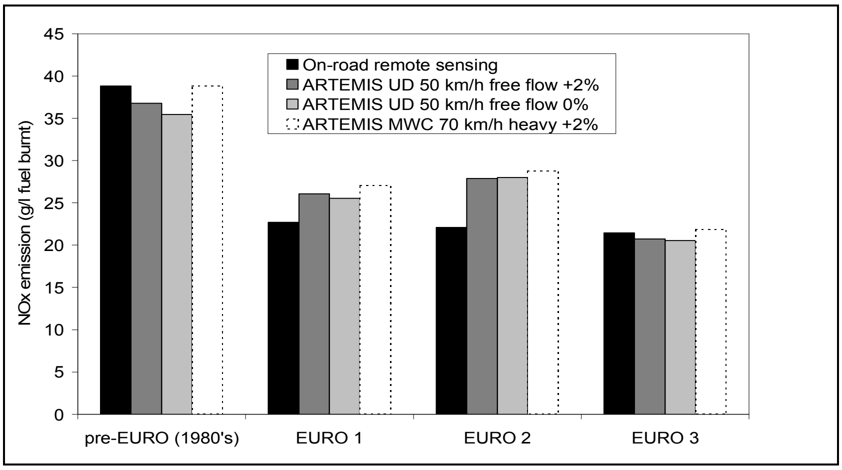


Figure G-13: NO_x emission factors for heavy goods vehicles (HGV) from remote sensing measurements and the ARTEMIS model (UD = Urban Distributor, MWC = Motorway City, 50/70 km/h = posted speed, free flow/heavy = level of service, %-figures = applied road grade according to ARTEMIS road model traffic situations definitions).

Conclusions

The project undertaken in Sweden has demonstrated how existing national road and traffic data can be allocated to the traffic situations in the ARTEMIS model. Eighty-five of the 276 ARTEMIS traffic situations were identified in Sweden in 2004. The study presented new figures concerning the distribution of traffic on urban and rural roads in Sweden. Furthermore, a model for estimating the distribution of urban traffic in cities of different sizes was developed. The overall methodology will be developed and refined in further research projects, as more simulated traffic data become available. The validation of the assumptions and methods to estimate the share of vehicle mileage under stop-and-go traffic conditions is another area for further research. The translation between Swedish road categories and ARTEMIS categories was mainly based on the description of road hierarchy, function and design, and speed limit. In further research the driving cycles associated with the various TSs will be compared with data on real-world driving patterns for the corresponding Swedish road categories.

There was also found to be a reasonable agreement between the ARTEMIS model and the national EMV model in terms of CO_2 emissions (present and historical), whereas for the regulated pollutants CO, HC, NO_x some significant discrepancies between the models were observed. The ARTEMIS model agrees well with on-road emission data, although the differences in HDV NO_x emissions between Euro I and Euro III vehicles predicted by the model was not confirmed by the on-road data.

G3 Rail transport model

The ARTEMIS rail transport model is described by Cordeiro *et al.* (2005). The model takes the form of a MicroSoft Excel spreadsheet that includes data from the GISCO database on railway traffic. The software is programmed in Visual Basic, and macros are accessible by loading the main Excel program '*Artemis_Rail.xls*' and selecting the Visual Basic editor within Excel. Cordeiro *et al.* (2005) provide information on how to run the model, and an overview on how it works. In addition, instructions are provided on how to update the underlying databases. This model is provided as a free, open-source program that the user can manipulate to fit the desired goals, and can update as new data are gathered.

Figure G-14 shows how different modules in the program interact with each other. The modules (solid line boxes) that are presented inside a dashed line box are called from the upper module in the box. For example, the module 'Rolling Resistance' will run the module 'Energy' internally. When the program is run, it will call module 'Main' and, according to the chosen calculation type ('All Trains' or 'Specific Trains'), different program paths are taken. When the emission calculations have been completed, the program will open the corresponding results sheet.

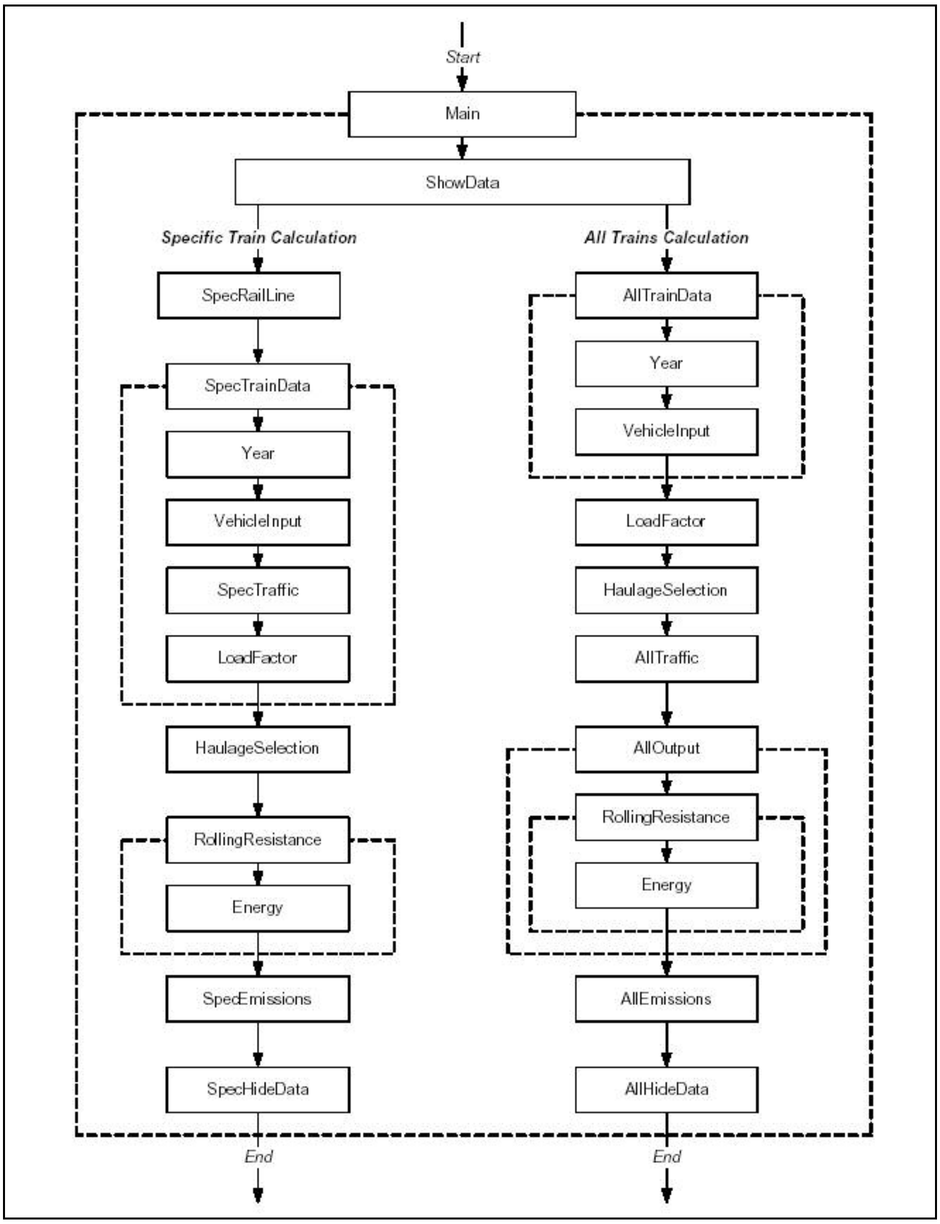


Figure G-14: Rail transport model schematic.

The traffic data in the model have been developed jointly with the TRENDS project, and the sources and methodologies have been reported in Georgikaki, *et. al.* (2002). In the current work, the detailed traffic data have been entered based on the INTRAPLAN study in the rail network in 1995. For the calculation of temporal trends, these data needed to be adjusted for changes in time. In the TRENDS work, the temporal trends in traffic were determined on a national level, using data from Eurostat and some other sources. In order to use these national changes in traffic on a local level, all the local traffic data were corrected using the same factor, which was determined by the national temporal changes in traffic, such as numbers of passengers, train-km, *etc*. The local traffic for all the routes in each country, where detailed data was available, was then corrected using the same factor for all local routes. Different factors were used for passenger and freight traffic in each country. The method should reflect the general trends in each country. However, given the open structure of the model, the user may choose to update the tables as additional results become available. Performance data for various types of trains and country-average figures are also included.

As rail traffic information changes every year, the user can input different traffic information data for each year. For passenger trains, the parameters which can change with time are the numbers of long distance and local trains per workday and the number of passengers per year. For freight trains, the traffic information that can change with time are the number of freight trains per workday and the weight transported per year.

Average route gradients are not inputted in the present version of the software (values are assumed to be zero). The user has two options for entering alternative values. The first option is to enter the start and end city altitudes, and the model automatically calculates the average gradient. The second option is to enter the average gradient directly. Different emission and load factors for the available countries can be entered for various years. The emission factors can be changed according to pollutant species and train type. The original default train data provides the user with mean values that will give a good approximation for an average train, but these can be changed by the user. New countries, and new routes for existing countries, can also be easily entered.

The quality of the data included in the database determines the overall accuracy of the energy consumption and emissions. The results given by the program are highly dependant on the input data, and this should be taken into consideration. The database can be updated to better reflect the countries involved, and special care must be taken to select the best country-specific emission and load factors, as they will be applied to each route.

G4 Inland shipping model

G4.1 Introduction

The first task in the development of the ARTEMIS inland shipping module involved a review of the vessel categorisations and the identification and adoption of the most suitable classification scheme. The scheme selected was based on the agreement of the European Ministers of Transport (ECMC, 1992) and should thus be compatible with most categorisations based on vessel size and type. Nine classes are established based on the vessel's size and the waterways it is able to navigate. Sub-classes further define the vessel type or the configuration of the pushed convoys.

The resulting simplified methodology allows users to follow a single vessel through a particular trip and estimate the energy consumption and emissions occurring in great detail. However, indicators produced for typical vessels also allow for estimations of the overall environmental burden based on the amount of traffic experienced across larger areas.

A technical model, which was previously partly developed under the MEET and TRENDS projects (Georgakaki *et al*, 2002), has been improved and validated using experimental data provided by the European Development Centre for Inland and Coastal Navigation. As the model is intended for non-expert users there is a provision for most of the parameters to be defaulted through appropriate correlations. Central to the development of this inland shipping model has been its validation. This was done for a wide variety of service conditions, giving priority to data arising from full-scale measurements. Those conditions that could not be covered by full-scale tests were covered by model towing-tank tests. The validation shows that the model on average has a good correlation with the experimental data, but the deviation can be considerable. Accuracy for the predicted engine output against measured values is between 80% and 107% with deviation ranging from 19% to 30%. The model performance is thus deemed acceptable for the purpose of the estimation of the average operation of the fleet.

Special focus was put on the specific fuel consumption of engines used on inland shipping vessels, as this was an area of considerable uncertainty. Using test data provided by the manufacturers, a correlation was developed to provide specific fuel consumption values according to the engine output. The uncertainty is thus greatly reduced as the values provided by the correlation are within the error margins given by the manufacturers. As with most other input parameters of the model, this correlation may be overridden by the user, through the use of specific and dedicated input data.

The model has subsequently been put to use to provide examples of indicators that may be produced for typical vessels in service under different conditions. These calculations give an idea of how the different parameters (speed, draught, waterway depth *etc*.) influence the energy consumption of inland vessels. More results are available through different projects (such as TREMOVE) that already incorporate the ARTEMIS inland shipping model.

The model requires the user to provide a range of input data, including average waterway width, depth, speed limits, the share of different vessels on the waterway, and their average load. The possibility of connecting the ARTEMIS model results to a GIS platform was examined. However, though possible on a theoretical basis, this connection could not be completed due to the lack of the necessary information in the present representation of the waterway network. With subsequent developments in this area, the future integration with GIS is now a reality.

A small review of measures aimed at reducing air pollutant emissions from inland vessels in future was also undertaken. In the case of sulphur oxides the effect of the measures will be immediate. However, for other pollutants, the measures proposed will only give results after a significant part of the fleets' engines have been replaced. Due to the long service lives of these engines and the time frame of the measures, the predictions given by the TRENDS project for the next 15 to 20 years will remain largely realistic, for the majority of pollutants.

G4.2 Model structure

Calculations based on the methodology developed for the estimation of energy consumption and emissions from inland shipping are performed within an MS Excel Spreadsheet. The structure of the model, described earlier in Part D, is further summarised in the folowing section, with full details available in the main task report byGeorgakaki and Sorensen (2004).

The model has two versions; one for calculating indicators for self propelled vessels and second, which is tuned to the calculation of indicators for pushed convoys. Furthermore for each version, two sub-versions exist giving bulk results either per vessel-kilometre travelled or per ton-kilometre of goods carried. This amounts to four files named:

- ARTEMIS – motorship.xls
- ARTEMIS – motorship+.xls
- ARTEMIS – convoy.xls
- ARTEMIS – convoy+.xls

The version number may be following the filename. The versions marked (+) provide bulk results per vessel-km travelled. Each excel workbook contains three sheets with similar structure named:

- Model
- Input
- Output

All of the model versions include a simple input data guide as shown in **Figure G-15**.

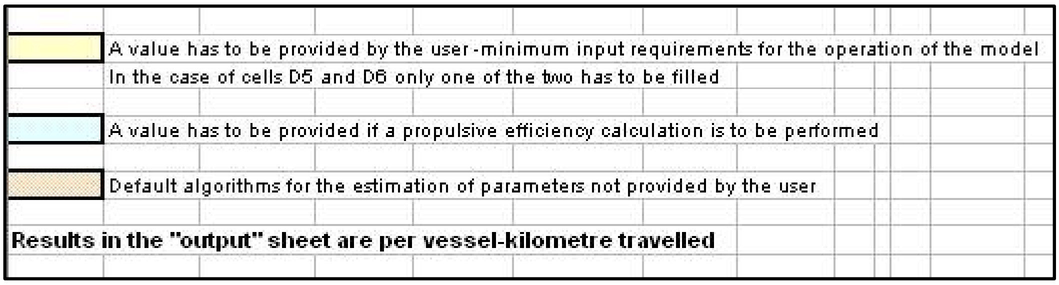
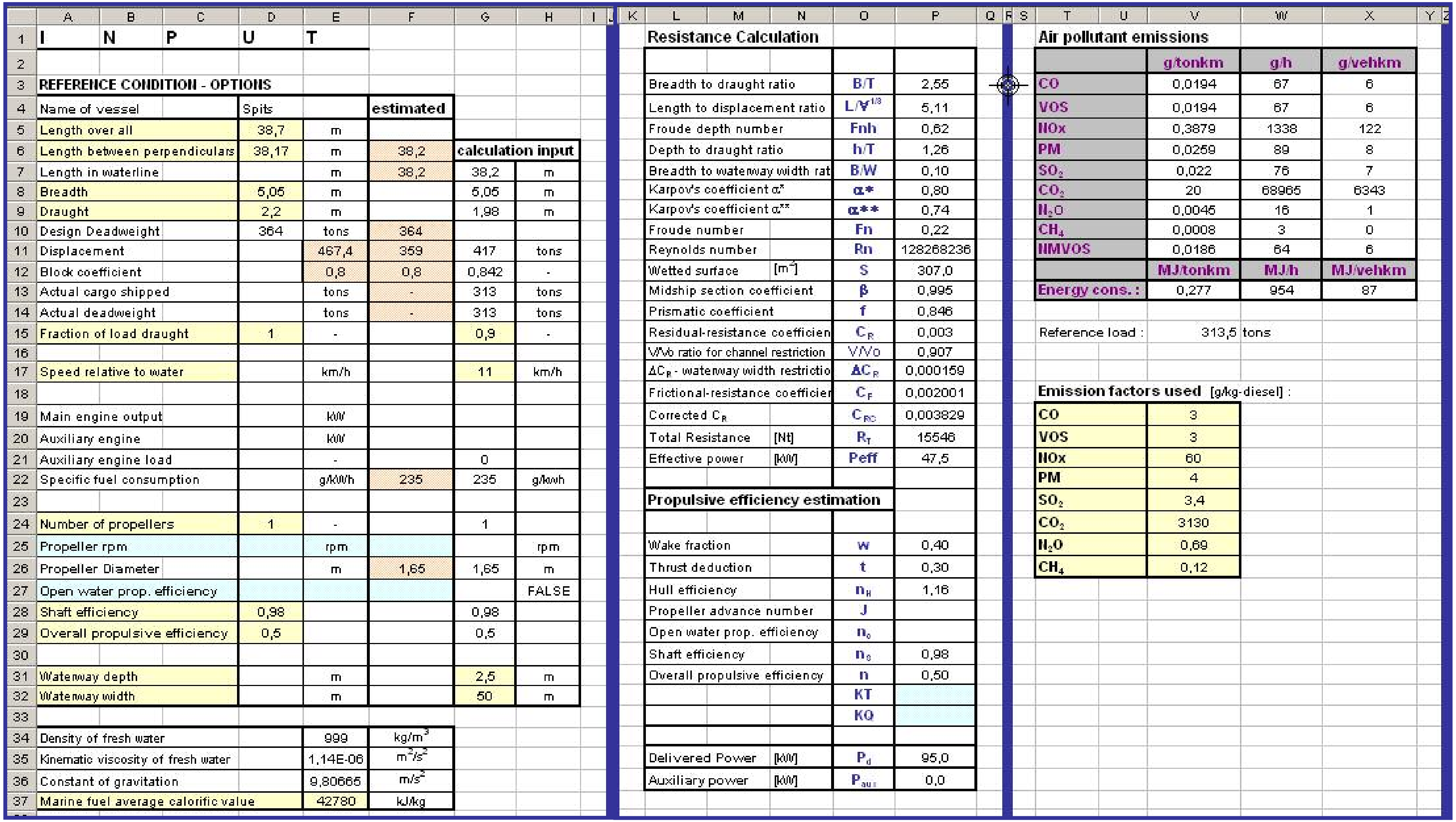


Figure G-15: Simple guide for user input included in the inland shippin model 'Vessel' Sheet.

An example of the 'Vessel' worksheet sheet can be seen in Figure G-16. It contains all the algorithms and parameters necessary for the emission calculation. The user is requested to provide input values, follow the calculation of intermediate parameters and obtain results per vessel-kilometre, ton-kilometre of goods carried and also per hour of sailing. To preserve the model structure all cells that are not receiving input values are password-protected (Sorenson 2006).



INPUT

Row	Parameter	Value	Unit	estimated	calculation input	Unit
3	REFERENCE CONDITION - OPTIONS					
4	Name of vessel	Spits				
5	Length over all	38,7	m			
6	Length between perpendiculars	38,17	m	38,2		
7	Length in waterline		m	38,2	38,2	m
8	Breadth	5,05	m		5,05	m
9	Draught	2,2	m		1,98	m
10	Design Deadweight	364	tons	364		
11	Displacement		467,4	359	417	tons
12	Block coefficient		0,8	0,8	0,842	-
13	Actual cargo shipped		tons	-	313	tons
14	Actual deadweight		tons	-	313	tons
15	Fraction of load draught	1	-		0,9	-
16						
17	Speed relative to water		km/h		11	km/h
18						
19	Main engine output		kW			
20	Auxiliary engine		kW			
21	Auxiliary engine load		-		0	
22	Specific fuel consumption		g/kWh	235	235	g/kwh
23						
24	Number of propellers	1	-		1	
25	Propeller rpm		rpm			rpm
26	Propeller Diameter		m	1,65	1,65	m
27	Open water prop. efficiency					FALSE
28	Shaft efficiency	0,98			0,98	
29	Overall propulsive efficiency	0,5			0,5	
30						
31	Waterway depth		m		2,5	m
32	Waterway width		m		50	m
33						
34	Density of fresh water		999	kg/m^3		
35	Kinematic viscosity of fresh water		1,14E-06	m^2/s^2		
36	Constant of gravitation		9,80665	m/s^2		
37	Marine fuel average calorific value		42780	kJ/kg		

Resistance Calculation

Parameter	Symbol	Value
Breadth to draught ratio	B/T	2,55
Length to displacement ratio	$L/\nabla^{1/3}$	5,11
Froude depth number	Fnh	0,62
Depth to draught ratio	h/T	1,26
Breadth to waterway width rat	B/W	0,10
Karpov's coefficient α^*	α^*	0,80
Karpov's coefficient α^{**}	α^{**}	0,74
Froude number	Fn	0,22
Reynolds number	Rn	128268236
Wetted surface $[m^2]$	S	307,0
Midship section coefficient	β	0,995
Prismatic coefficient	f	0,846
Residual-resistance coefficien	C_R	0,003
V/Vo ratio for channel restriction	V/Vo	0,907
ΔC_R - waterway width restrictio	ΔC_R	0,000159
Frictional-resistance coefficier	C_F	0,002001
Corrected C_R	C_{RC}	0,003829
Total Resistance [Nt]	R_T	15546
Effective power [kW]	Peff	47,5
Propulsive efficiency estimation		
Wake fraction	w	0,40
Thrust deduction	t	0,30
Hull efficiency	n_H	1,16
Propeller advance number	J	
Open water prop. efficiency	n_o	
Shaft efficiency	n_s	0,98
Overall propulsive efficiency	n	0,50
	KT	
	KQ	
Delivered Power [kW]	P_d	95,0
Auxiliary power [kW]	P_{aux}	0,0

Air pollutant emissions

	g/tonkm	g/h	g/vehkm
CO	0,0194	67	6
VOS	0,0194	67	6
NOx	0,3879	1338	122
PM	0,0259	89	8
SO_2	0,022	76	7
CO_2	20	68965	6343
N_2O	0,0045	16	1
CH_4	0,0008	3	0
NMVOS	0,0186	64	6
	MJ/tonkm	MJ/h	MJ/vehkm
Energy cons. :	0,277	954	87

Reference load : 313,5 tons

Emission factors used [g/kg-diesel] :

CO	3
VOS	3
NOx	60
PM	4
SO_2	3,4
CO_2	3130
N_2O	0,69
CH_4	0,12

Figure G-16: An example of the inland shipping 'Vessel' sheet, where individual calculations may be performed.

The input of the engine capacity does not influence the calculation but acts like a reference point for the service conditions obtainable. The following provides a list of outputs available from the model:

- Code
- Speed
- Pd (delivered power)
- % (load on the main engine)
- Fn (Froude number)
- Fnh (Froude depth number)
- h/T (waterway depth to vessel draught ratio)
- b/bc (vessel breadth to waterway width ratio)
- L/D (length to displacement ratio – M)
- φ (prismatic coefficient)
- SFC (specific fuel consumption in g/kWh)
- J (advance number)
- np (propulsive efficiency)
- EC (energy consumption in MJ per ton-km or vessel-km)
- CO (emission in grams per ton-km or vessel-km)
- VOC (emission in grams per ton-km or vessel-km)
- NO_X (emission in grams per ton-km or vessel-km)
- PM (emission in grams per ton-km or vessel-km)
- SO_2 (emission in grams per ton-km or vessel-km)
- CO_2 (emission in grams per ton-km or vessel-km)
- N_2O (emission in grams per ton-km or vessel-km)
- CH_4 (emission in grams per ton-km or vessel-km)
- NMVOC (emission in grams per ton-km or vessel-km)

G5 Maritime shipping model

The ARTEMIS emission model for Maritime shipping was described in Part E of the Report. The model provides two main approaches for determining the fuel consumption and emissions for a particular vessel type. The first approach - the 'simple method' - involves the use of the ship's type and size to look up emission values in a static table. The second approach - the 'detailed method' – can be used if more information is available, and also involves average speed, the main engine power output and the main engine type. Two further considerations apply: emissions associated with the effects of auxiliary engines in port, and the effects of emission-control equipment.

No actual software was produced within ARTEMIS, and for any calculations the user must refer to the equations and tabulated data which are given in Part E.

G6 Air transport model

Three main classes of air transport can be distinguished when analysing its operational and emission related characteristics:

- flights performed under Instrument Flight Rules (IFR),
- military operational air traffic,
- flights performed under Visual Flight Rules (VFR).

There are some minor overlaps between the classes. However, each category has its own typical data set available for traffic characteristics and engine emissions, so it is considered appropriate to base the methodology for estimating exhaust emissions on these three classes.

In contrast to the other transport modes explored within the ARTEMIS project, the outputs of the aviation work package have resulted in an addendum to an existing model, rather than an entirely new approach. Indeed the basic objective within the aviation work package was to close the gaps between the air traffic emissions research community and the typical user of methodologies for air traffic emission inventories. Knowledge on emission characteristics has been improved in recent years mainly through European Union sponsored research projects such as POLINAT and AEROCERT. However, much of the output from these research projects have not yet been released for use by the wider modelling community, including national inventory tools such as CORINAIR. The ARTEMIS project attempted to identify existing knowledge, undertake a gap analysis and update the existing emission database and modelling tools contained within the tools developed under the earlier MEET and TRENDS projects (Kalivoda and Bukovnik, 2007).

In particular, the ARTEMIS project focussed on the following:

- The influence of maintenance and ageing of engines on emissions,

- Aircraft/engine combinations not covered in the current database, *e.g.* turbo props, new airframes or former Soviet aircraft.
- Allocation of emissions. Current international reporting mechanisms only ask for domestic and ground related emissions, which are emissions below 3000 feet. Emissions from international flights above 3000 feet are not allocated. The allocation procedure will have a significant influence on the general methodology for emission calculation
- in-flight situation (focusing on the influence of cruise ambient temperatures on emissions). A lot of in-flight emission data has been and still is collected within CEC sponsored projects such as POLINAT, AEROTRACE and AEROCERT. However, these results are not included in most of the currently used emission inventory tools.
- Ground-based operations. Emissions from engine start are not included in the LTO-cycle but will have a significant influence on total VOC emissions of aviation, as well as on local air quality around airports.

Therefore the ARTEMIS project undertook a range of new measurements of NO_X, NO_2, N_2O, CO, HC, CH_4, SO_2 as well as PM_{10} emissions from aircraft engines on the ground, investigated the effect of ambient conditions and level of maintenance, and compiled all available emission data. This activity allowed the generation of new emission factors for APUs and turbojets.

The main objective was the development and enhancement of an improved air transport emission database and model. The emphasis was the amalgamation of existing data, rather than a campaign of new emission measurements. Within ARTEMIS a new emission model was created for APUs, as an extension to the TRENDS methodology for the TABs generation.

The approach for air traffic emission modelling is bottom-up, rather than the top-down methodologies used for the other transport modes. This is due to the complexity of traffic data availability, for instance from Eurocontrol where all the air traffic movements controlled by air traffic services (ATS) are recorded including essential information for estimating operational conditions. In order to produce emission forecasts for the time period 2002-2020, the traffic increase rates of 2002 – 2009 predicted by Eurocontrol (according to the baseline scenario) were extrapolated up to the year 2020.

Within the TRENDS database there are two main approaches:

• AvioPOLL: 1996-2002
• TABS: 1970-2020

The activity data which feeds into AvioPoll is the aggregated number of flights per origin/destination pairs per aircraft type groups. Therefore it has not been foreseen to allow the user to change any of this activity data in AvioPoll. The scenario testing is thus achieved within the transport activity balance (TAB) module. The results produced by TAB can be divided into two main categories: Traffic activity and emission results. These results are given per country for all the years considered by TRENDS. A large number of options are available to the user for implementing these results. Data produced by TAB can be displayed according to the traffic type (passenger/freight), according to the vehicle type and the vehicle technology.

The ARTEMIS programme has resulted in APU-data provided in such a way that they can be implemented within the TRENDS database (Kalivoda and Bukovnik, 2007). For an average flight within the Eurocontrol area, an example of APU-emissions were generated, which are shown in **Table G-5**.

Fuel (kg/h)	HC (g)	CO (g)	NOx (g)
114,88	57,36	962,65	756,06

Table G-5: APU-emissions for one single flight with the Eurocontrol Area - Average emissions per movement (Kalivoda and Bukovnik, 2007).

Finally, outputs from this supplementary TRENDS model for APU-data are produced for a time period from 1970 up to 2015. Emissions were generated for each year and country according to the Eurocontrol, and subdivided into short, medium and long haul. **Table G-6** provides an example of APU-TABs generation.

	Mode	Year	Country	TrafficType	Subsegment	Movements	Fuel (kg/h)	HC (g)	CO (g)	NOx (g)
0	AIR	1970	AT	Passenger	**Short Haul**	14.554	1671907,51	834888,3877	14010506,18	11003790,88
1	AIR	1971	AT	Passenger	**Short Haul**	15.526	1783610,116	890668,5121	14946568,76	11738970,38
2	AIR	1972	AT	Passenger	**Short Haul**	16.499	1895312,723	946448,6366	15882631,34	12474149,87
3	AIR	1973	AT	Passenger	**Short Haul**	17.471	2007015,329	1002228,761	16818693,92	13209329,37
4	AIR	1974	AT	Passenger	**Short Haul**	18.444	2118717,936	1058008,886	17754756,5	13944508,87
5	AIR	1975	AT	Passenger	**Short Haul**	18.848	2165177,204	1081208,915	18144082,97	14250284,2
6	AIR	1976	AT	Passenger	**Short Haul**	20.534	2358903,585	1177948,66	19767500,92	15525309,63
7	AIR	1977	AT	Passenger	**Short Haul**	21.427	2461464,611	1229163,819	20626957,49	16200323,09
8	AIR	1978	AT	Passenger	**Short Haul**	23.213	2666586,661	1331594,137	22345870,61	17550350,01
9	AIR	1979	AT	Passenger	**Short Haul**	24.602	2826126,034	1411262,163	23682803,04	18600370,95
10	AIR	1980	AT	Passenger	**Short Haul**	25.395	2917291,39	1456786,748	24446764,43	19200382,92
11	AIR	1981	AT	Passenger	**Short Haul**	24.899	2860313,043	1428333,882	23969288,56	18825375,44
12	AIR	1982	AT	Passenger	**Short Haul**	24.304	2791939,026	1394190,443	23396317,52	18375366,46
13	AIR	1983	AT	Passenger	**Short Haul**	25.395	2917291,39	1456786,748	24446764,43	19200382,92
14	AIR	1984	AT	Passenger	**Short Haul**	27.181	3122413,441	1559217,067	26165677,55	20550409,84
15	AIR	1985	AT	Passenger	**Short Haul**	28.768	3304744,153	1650266,238	27693600,33	21750433,77
16	AIR	1986	AT	Passenger	**Short Haul**	31.149	3578240,221	1786839,996	29985484,49	23550469,67
17	AIR	1987	AT	Passenger	**Short Haul**	32.538	3737779,594	1866508,021	31322416,92	24600490,61
18	AIR	1988	AT	Passenger	**Short Haul**	33.829	3886107,098	1940577,257	32565394,42	25576719,76
19	AIR	1989	AT	Passenger	**Short Haul**	38.483	4420784,559	2207575,282	37045966,36	29095741,55
20	AIR	1990	AT	Passenger	**Short Haul**	41.165	4728908,758	2361441,04	39628032,63	31123685,22
21	AIR	1991	AT	Passenger	**Short Haul**	45.456	5221753,083	2607549,154	43758044,86	34367378,95
22	AIR	1992	AT	Passenger	**Short Haul**	51.266	5889245,234	2940869,892	49351597,64	38760531,08
23	AIR	1993	AT	Passenger	**Short Haul**	55.352	6358636,536	3175266,439	53285074,64	41849866,88
24	AIR	1994	AT	Passenger	**Short Haul**	58.745	6748405,193	3369902,4	56551317,63	44415159,98
25	AIR	1995	AT	Passenger	**Short Haul**	65.352	7507320,021	3748876,221	62910988,14	49410017,65
26	AIR	1996	AT	Passenger	**Short Haul**	83.378	9578106,159	4782949,751	80264078,43	63039059,62
27	AIR	1997	AT	Passenger	**Short Haul**	82.959	9529973,241	4758913,963	79860726,84	62722269,03
28	AIR	1998	AT	Passenger	**Short Haul**	83.003	9535027,772	4761438,007	79903083,57	62755535,82
29	AIR	1999	AT	Passenger	**Short Haul**	80.302	9224748,505	4606496,089	77302957,92	60713408,4
30	AIR	2000	AT	Passenger	**Short Haul**	88.895	10211875,4	5099430,522	85575034,8	67210261,76
31	AIR	2001	AT	Passenger	**Short Haul**	81.489	9361105,961	4674587,928	78445626,99	61610855,74
32	AIR	2002	AT	Passenger	**Short Haul**	26.607	3056497,764	1526301,231	25613307,28	20116580,63
33	AIR	2003	AT	Passenger	**Short Haul**	26.607	3056497,764	1526301,231	25613307,28	20116580,63
34	AIR	2004	AT	Passenger	**Short Haul**	27.325	3138978,517	1567489,049	26304492,11	20659434,19
35	AIR	2005	AT	Passenger	**Short Haul**	27.598	3170339,583	1583149,599	26567296,37	20865839,52
36	AIR	2006	AT	Passenger	**Short Haul**	27.873	3201930,401	1598924,877	26832025,93	21073756,97
37	AIR	2007	AT	Passenger	**Short Haul**	28.123	3230649,326	1613266,04	27072689,17	21262772,84
38	AIR	2008	AT	Passenger	**Short Haul**	28.657	3291992,95	1643898,762	27586745,85	21666510,73
39	AIR	2009	AT	Passenger	**Short Haul**	28.599	3285330,16	1640571,613	27530911,98	21622659,05
40	AIR	2010	AT	Passenger	**Short Haul**	29.024	3334145,95	1664948,402	27939986,01	21943944,02
41	AIR	2011	AT	Passenger	**Short Haul**	29.317	3367823,677	1681765,805	28222203,76	22165596,62
42	AIR	2012	AT	Passenger	**Short Haul**	29.610	3401501,403	1698583,208	28504421,52	22387249,23
43	AIR	2013	AT	Passenger	**Short Haul**	29.903	3435179,129	1715400,611	28786639,28	22608901,84
44	AIR	2014	AT	Passenger	**Short Haul**	30.197	3468856,855	1732218,014	29068857,04	22830554,44
45	AIR	2015	AT	Passenger	**Short Haul**	30.490	3502534,581	1749035,417	29351074,8	23052207,05
46	AIR	2016	AT	Passenger	**Short Haul**	30.827	3541232,614	1768359,775	29675362,49	23306901,2
47	AIR	2017	AT	Passenger	**Short Haul**	31.128	3575851,648	1785647,232	29965468,36	23534749,09
48	AIR	2018	AT	Passenger	**Short Haul**	31.429	3610470,682	1802934,689	30255574,24	23762596,99
49	AIR	2019	AT	Passenger	**Short Haul**	31.731	3645089,715	1820222,146	30545680,11	23990444,88
50	AIR	2020	AT	Passenger	**Short Haul**	32.032	3679708,749	1837509,603	30835785,98	24218292,78

Table G-6: An example of APU-emission estimates (1970-2020), using the TRENDS-ARTEMIS TABs generator (Kalivoda and Bukovnik, 2007).

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PART H: SUMMARY AND RECOMMENDATIONS

H1 Project background, objectives and scientific co-operation

ARTEMIS was conceived to address the need to develop a harmonised emission model for road, rail, air and ship transport, and to provide consistent emission estimates at the national, international and regional levels. The project commenced in 2000, and had two principal objectives. The first of these was to gain, through a large programme of basic research, a better understanding of the uncertainties in emission modelling. For road transport, measurements conducted in many laboratories around Europe were used to examine the reasons for variability in the data, and to provide guidance on future measurements. The models for non-road transport modes were also greatly improved. The second principal objective was to develop a harmonised methodology for estimating emissions from all transport modes at the national and international levels. This Report has presented a summary of the findings of the ARTEMIS research, and has described the resulting inventory model.

The specific objectives of ARTEMIS can be summarised as follows:

(i) To extend existing emission models, their underlying data, and their methodologies, so that they will be able to incorporate not only the known influential parameters, but also future emission factors which might require additional external information (*e.g.* use of air conditioning devices, new engine or pollution control concepts).

(ii) To make emission models and inventories more consistent between applications at different levels of spatial resolution. This included both the types of emission factor to be applied and the description of traffic characteristics.

(iii) To improve co-ordination, increase efficiency, and generally make better use of available resources, information and tools. At the outset, it was considered that some of the reasons for the discrepancies between different emission models might be institutional in nature, such as the lack of communication and the use of different databases describing the same phenomena. In order to achieve a higher level of consistency, ARTEMIS established a research group (ETERG) to improve the co-ordination of the research activities and to enable better access to national data as a prerequisite for more consistent inventories.

(iv) To better validate emission models in order to improve inventories and their underlying emission factors, and to improve credibility.

(v) To make information available to a broad range of users in the form of a user-friendly tool.

ARTEMIS was a large and very diverse project which benefited from the participation of a large consortium, including many of the relevant key organisations in Europe. The project consortium was made up of 37 partners from 14 countries. The project was co-ordinated by TRL Limited, with assistance from a project co-ordination committee comprising the individual work package leaders, plus the project coordinator from the PARTICULATES project. For each main aspect of the ARTEMIS work, the summary and, where appropriate, the recommendations are provided below.

H2 Road transport

H2.1 Road traffic characteristics

Summary

The road traffic characteristics required for the estimation of emissions constitute a considerable field of investigation, and have received poor coverage to date. The uncertainty in emission estimates remains strongly associated to the traffic-related parameters, which are themselves often highly uncertain.

Although traffic statistics were available from studies prior to ARTEMIS (*e.g.* MEET, TRENDS), their quality and applicability were questionable. For better forecasts of vehicle fleets and usage, the existing approaches needed to be improved and validated. As part of ARTEMIS and COST346, comprehensive studies of road traffic characteristics were performed in order to address these issues. The work has enabled significant progress in this area, with the main achievements including the following:

(i) *A review of existing information on road traffic characteristics*. Careful consideration was given to the data requirements for emission models, and to the needs of model users.

(ii) *A review of traffic data requirements.* Before the collection of data began, an analysis was conducted to assess and rank the relative influences of different traffic parameters on emissions. This was achieved through a literature review, and through the processing of existing data.

(iii) *Data collection*. Road transport statistics from national and international databases were collated, including information on traffic activity, trip lengths, engine temperatures, speeds, driving patterns and traffic composition.Tools and protocols were also developed for the management of data (databases, software, *etc*.).

(iv) *A review of sensitivity analysis studies*. An in-depth analysis of the COPERT methodology, including the identification of sources of uncertainty, was conducted. Furthermore, a range of factors relating to traffic data requirements, user expectations and modelling difficulties were considered.

(v) *The classification of road traffic*. This involved the collection, processing, assessment and application of the road transport data. The results helped to define the ARTEMIS emission model for road transport, and provided direct inputs into it. A traffic situation modelling approach was defined for use in ARTEMIS, as well as a conventional average-speed approach. This required the characterisation of driving patterns corresponding to a range of traffic situations. Traffic structures, and parameters that have to be considered in the estimation of pollutant emissions from the road transport (vehicle fleet, definition of traffic situations), were identified.

(vi) *The collection of data for each of the defined traffic situations and vehicle categories*. Data relevant to the traffic situation modelling approach - such as avergae speed and representative driving patterns - were collected. Several studies also collated existing statistics relating to parameters such as the load factors, annual mileages, vehicle survival rates, speed, *etc*. Although not directly applicable within the ARTEMIS tool, these studies have clearly indicated gaps in the data and have identified the pertinent parameters. They were used as a basis for constituting default datasets for the emission estimation tools.

(vii) *A specific investigation in the Central and Eastern European countries* This revealed large gaps and a number of inconsistencies in the traffic data, but represented a useful starting point for further work.

Recommendations

Further work is recommended on the following topics:

- The provision of reliable and detailed speed data for different vehicle categories and the large number of traffic situations that have been defined.
- The validation of emission estimation approaches at different scales, particularly in relation to the traffic data needed at these scales.
- The derivation of default values for important parameters, such as load factors and survival rates, using the data and findings of the ARTEMIS programme.

H2.2 Passenger cars

Summary

The emissions associated with passenger cars were investigated within WP300 (Joumard *et al*., 2006, 2007). The work was conducted in three main Phases:

Phase 1 An assessment of the accuracy of emission measurements.
Phase 2 The improvement of the European database of measurements used for model development.
Phase 3 The development of new emission models.

Eleven European laboratories worked together to study the influence of many parameters on the measurement of light vehicle emission factors. The overall aim was to improve the accuracy, reliability and representativeness of the emission factors. The parameters studies included driving patterns (driving cycles, gear choice behaviour, driver and cycle following), vehicle-related parameters (technical characteristics of the vehicle, emission stability, emission degradation, fuel properties, vehicle cooling and preconditioning), vehicle sampling (method, sample size), and laboratory-related parameters (ambient temperature and humidity, dynamometer setting, dilution ratio, heated line sampling temperature, PM filter preconditioning, response time, dilution air). The results were based upon a combination of literature reviews, around 2,700 specific tests on 183 vehicles, and on the reprocessing of data from more than 900 earlier tests. These tests concern the regulated atmospheric pollutants and pre-Euro I to Euro IV vehicles.

The emission models for light-duty road vehicles have been updated and greatly improved in ARTEMIS. This development was based on a targeted, in-depth measurement campaign, with more than 150 vehicles and about 3,500 tests for a large number of pollutants, both regulated and unregulated.

ARTEMIS followed on from, and was designed to replace, the two main inventory models in use in Europe - MEET/COPERT III and the Handbook of Emission Factors (HBEFA), mainly used in Austria, Germany and Switzerland. In the ARTEMIS project, the most recent and comprehensive data on emissions were used to further develop a set of complementary sub-models. The base model calculates hot emissions for each vehicle category according to driving behaviour. It contains five alternative models:

- The main model considers traffic situations, with emission factors for each traffic situation.
- A simplified model, built on the same data, takes into account driving behaviour through average speed.
- A so-called kinematic model considers a limited number of aggregated kinematic parameters
- Two instantaneous models, which use a number of instantaneous vehicle operation parameters.

The results of the measurements carried out by several European laboratories are included in a database specially designed for the project - the ARTEMIS LVEM database – to which can be added future European measurements.

Recommendations

- ARTEMIS developed and adopted a real world driving cycle (CADC), which is recommended for future exhaust emission measurement campaigns. The use of common cycles within national emission test programmes will more readily allow the development of harmonised European emission factor databases and models, through the ready exchange of emission data.
- The ARTEMIS emission test programme incorporated the development of a recording data management protocol. This protocol is recommended for use in future emission measurement programmes.
- For seven emission measurement test cell parameters no systematic effect on emissions was observed, and only a qualitative effect could be stated for seven other parameters. However, six parameters had a clear and quantifiable on emissions and for five of these correction factors could be developed to normalise emission measurements: gearshift strategy, vehicle mileage, ambient temperature and humidity, dilution ratio. The sixth influencing parameter was the driving cycle, which was sometimes more significant than the fuel or the emission standard. The results led to a series of recommendations and guidelines for the determination of light-duty road vehicle emission factors in the future.
- The ARTEMIS project resulted in the development of five emission modelling approaches for light duty vehicles. These models are recommended for use in future emission modelling exercises, and national reporting requirements.
- ARTEMIS identified the importance of ancillaries to fuel consumption and emissions. Whilst this study identified the magnitude of this effect, uncertainty remains over the number of vehicles equipped with ancillaries, and the ways in which these are used, across the EU. Further work is thus required to characterise the usage of these ancillaries.
- Further work is required to characterise the importance of gradient across the European Union, both in terms of geographic mapping and road length characteristics, but also the effect on fuel consumption and emissions. In addition the effect of load requires further investigation.
- Finally ARTEMIS investigations concentrated on conventional road fuels, and thus more work is recommended to evaluate the energy and emissions associated with new fuels and power trains. For this reason, the ARTEMIS database and models have been designed to allow the incorporation of new vehicle classes, technologies and emission data.
- Significantly, based upon the results from the early generation of particulate filters, it is vital that future emission measurements also seek to identify the knock-on effects of technologies such as the increase in primary NO_2 from catalytic particulate traps, and the potential for increased ammonia emissions with SCR.

H2.3 Light commercial vehicles

Summary

Emission factors for LCVs were included in COPERT III, but the method was based on data obtained from passenger cars. Furthermore, only pre-Euro I and Euro I vehicles were included in COPERT III, the emission factors only took into account average speed (via regression fits to the data), and the values of the coefficients of determination for the regression functions were rather low. In ARTEMIS, actual data for LCVs were extracted from the database of measurements, and subsequently used to develop new emission factors which took into account both average vehicle speed and load.

The database included 150 vehicles tested, and over 2,035 cycles. Specific driving cycles for LCVs were also developed for the programme. These cycles took into account not only vehicle usage but also load factors. Vehicles were also classified according to emission standard (pre-Euro I to Euro III), and the type of fuel used (diesel, petrol). A total of 24 different vehicle classes were identified.

Recommendations

Further work is recommended on the following topics:

- The quantity of emission data from this segment of the fleet has been relatively poor. This most recent investigation by INRETS has added significantly to the characterisation of LCV emissions. However, these new emission measurements do not include the latest emission standards and technologies, and thus additional measurements are required.
- Remote sensing surveys continue to identify LCVs as having relatively high emissions.
- Given the specific types of services undertaken by LCV, consideration should be given to the development and use of a specific dedicated driving cycle, for use in subsequent emission measurement programmes.
- An assessment of the use and significance of a range of ancillaries including air conditioning, refrigeration units and motors should be undertaken.

H2.4 Heavy-duty vehicles

Summary

The main objectives of the HDV work were to collect a large amount of HDV emission data from European sources, to develop a model capable of accurately simulating emission factors for all types of HDV over any driving cycle and for various vehicle loads and gradients, to acquire the necessary model input data, and to generate a database of emission factors for the ARTEMIS inventory model. All these objectives were achieved in full, and the ARTEMIS work provided new insights into the emission behaviour of modern HDVs.

The resulting tool - PHEM - estimates fuel consumption and emissions (CO, THC, NO_x and PM) based on the instantaneous engine power demand and engine speed during a driving cycle specified by the user. The model combines steady-state engine maps with correction functions for transient operation. The transient correction function represents the main model asset for achieving high accuracy. Existing formulae were used to predict, with reasonable accuracy, the changes in emissions due to different fuel properties, although the effects were actually rather small.

The measurement programme and the method developed for the simulation of HDV emission factors proved to be capable of handling new engine technologies, as well as the various demand of model users. The collection of existing data and the measurement programme clearly benefited from co-operation with COST 346, HBEFA and national activities. Without this co-operation the number of available measurements would have been much smaller.

Since the introduction of the Euro I standard, NO_x emission levels for real-world driving conditions have not decreased as much as might have been predicted from the type approval limits. The main reason for this is the more sophisticated technologies being used for engine control and fuel injection, which allow different specific optimisation over different regions of the engine map. Fuel efficiency clearly has a much higher market value than low real-world emissions. Since the market situation encourages manufacturers to optimise fuel consumption wherever possible, the old ECE-R49 type approval test was not able to guarantee low NO_x emissions for the new generation of electronically controlled engines (post 1996). This situation improved with the introduction of the ESC test for Euro II.

Current HDVs exhibit stable emission behaviour during their lifetimes. However, this may change with the introduction of more sophisticated emission-control technologies in the near future. Since engine technology has progressed quite rapidly since 1996, and a further technological leap will be required for Euro IV and Euro V, it cannot be sure that the combination of the ESC and ETC cycles in the current type approval test will prevent real-world emission levels being significantly higher than at type approval. The type approval limits and test procedure have to be well-balanced to produce cost-effective benefits for air quality. Only lowering the limit values clearly gives an incentive to introduce off-cycle optimisation.

Recommendations

Due to the large and non-linear effects on emissions of vehicle size and vehicle load, as well as the effects of the driving cycle and the road gradient, the use of simple speed-dependent regression functions for the basic emission factors, and correction factors for gradient and load, is not recommended where high accuracy is required. PHEM should be used when accurate predictions are required.

A dedicated type approval test for existing technologies may soon have shortcomings for future technologies. Thus, in-use tests on the complete vehicle, based on random real-world driving and using on-board or test bed emission measurements, may be an important tool in the future if low emissions are to be guaranteed. Such in-use tests could also be used to check the durability of the new technologies introduced for Euro IV and Euro V. Such tests would have to be performed in time to enable action to be taken within the production lifetime of the vehicles. This does mean, however, that such a programme would have to commence immediately.

An update of the PHEM emission factors is recommended as soon as Euro IV and Euro V vehicles enter the market. Regular updates of the emission factors for actual HDV technologies will be highly important, especially for monitoring compliance with existing European emission and air quality targets for NO_x and PM_{10}. The emission behaviour of Euro IV and Euro V vehicles is very hard to predict at the moment, since the technologies used are new and no production vehicles were available for measurement. In-use tests could also be used to feed PHEM with data, as long as the test programme is designed accordingly. Such an approach could lower the cost of updates significantly, since measurements on the engine test bed for in-use Euro V HDVs may become very expensive due to the complex technology. Moreover, engine tests without special engine control units may be impossible for future heavy-duty engines, and thus new methods are necessary if tests which are independent from the manufacturers are to be performed.

H2.5 Two-wheel vehicles

Summary

When the ARTEMIS project began, only a few emission models were available for two-wheel vehicles. Models generally used the HBEFA methodology, which was based on emission tests on 24 motorcycles, mainly conducted in Switzerland, and all before 1996. More recent emission data were available, but these tended to be based on the type approval cycle for cars

(UDC) and relatively new motorcycles. The representativeness of these test results was therefore in doubt. Because of the diversity of motorcycles and their potential for high speeds and high accelerations, real-world driving was considered to be significantly different from that defined in the UDC. Additional measurements on in-use vehicles over real-world test cycles were therefore required.

One of the main objectives of ARTEMIS was to develop a new set of representative emission factors for two-wheel vehicles. An extensive measurement programme was conducted, involving tests on 90 motorcycles. The work focused on motorcycles with an engine capacity greater than 50 cm^3. The programme included a representative selection of vehicles and real-world test cycles, together with a representative gear-shift model and a road-load simulation procedure which corresponded to real-world conditions. Before the measurement programme began, a 'round-robin' test programme was carried out to check whether the emission results over different test cycles were reproducible when measured at different laboratories, and to identify potential measurement difficulties. The effects on emissions of cold starts, fuel properties and inspection and maintenance were also examined.

Since only limited real-world motorcycle driving measurements were available for ARTEMIS, available test cycles were used for the purpose of deriving representative emission values, and no new dedicated test cycles were developed. When real-world passenger car and motorcycle driving were compared, the main differences were at higher average speeds. At higher speeds the driving of two-wheel vehicles is much more dynamic than that of passenger cars due to the relatively high power:mass ratio. The CADC for passenger cars is very dynamic, and for urban driving has appropriate values of RPA and average acceleration for motorcycles. It was therefore included in the main measurement programme of ARTEMIS. In addition, the real-world test cycles of FHB were included in order to get an indication of the emissions produced during test cycles that originated from speed-time data recorded with a motorcycle.

Two-wheel vehicles were categorised based upon engine capacity, engine type, the presence of a catalyst, age and model class. Available fleet data were used for selecting vehicles for the measurement programme. In total, 115 motorcycles were tested according to the measurement protocol. Since the tests were carried out in 2002, only vehicles that complied with emission limits prescribed in Directive 97/24/EC Stage 1 and ECE Regulation R40 were tested. A relatively small proportion (12%) of the motorcycles tested were equipped with a catalyst. The participants noted that it was difficult to obtain small two-stroke scooters that were equipped with direct-injection systems and oxidation catalysts. NO_x emissions from two-wheel vehicles were very low over the type approval cycle. For motorcycles having high CO and HC emissions, the differences between the results over the type approval and real-world cycles were negligible. As emission levels over the type approval test decreased, the differences increased, but this ws not the case for $NO_{x.}$ Some of the tested motorcycles were equipped with an emission-control system which appeared to have been specifically calibrated for the type approval cycle. Emissions over the CADC urban and rural parts were higher than emissions over other test cycles, and it appeared that the differences were related to driving dynamics. However, for motorcycles equipped with exhaust gas after-treatment systems (Euro III), driving dynamics appears to be a less reliable determinant of emissions.

Cold-start emission factors were calculated using the results over the pre-conditioning cycles used for type approval. There were wide variations in cold-start emissions, even within a vehicle category. For some motorcycles, negative cold-start emission factors were observed for CO and HC. As the emission limit decreased, the contribution of the cold-start CO and HC to the total emissions increased. NO_x emissions appeared to increase for newer vehicles with lower cold-start CO and HC emissions. In order to assess the effects of fuel properties in ARTEMIS, an existing (Hungarian) market fuel and a fuel meeting the WWFC Category 4 future requirements were selected. Based on the results from the five motorcycles tested, if the market fuel were to be replaced by a fuel that was compliant with WWFC4 requirements, there would be a 15% reduction in CO emissions, a 5% reduction in HC emissions and a 4% increase in CO_2 emissions. NO_x emissions and fuel consumption would not be affected. The effects of inspection and maintenance were determined for seven motorcycles. For two motorcycles extensive repairs were needed. For one motorcycle maintenance had an adverse effect, with increases in emissions of between 1% and 18%, depending on the pollutant. For specific repairs, such as the replacement of a faulty battery, large improvements in emissions were observed. The effect of specific inspection and maintenance on emissions should therefore not be neglected.

The ARTEMIS model was based on large numbers of bag and on-line emission measurements. In total, about 2,700 emission results were available for emission modelling. Compared with the information that was previously used in former two-wheel vehicles emission models, this represented an enormous amount of data. A significant number of emission measurements from external sources were added to the ARTEMIS database, but the database contained only a few emission results for Euro II and Euro III motorcycles. The modelling methodology that was developed for HBEFA was also employed for ARTEMIS, including the vehicle categorisation. The ARTEMIS model is able to provide hot emission factors for several vehicle categories at three levels of output: (i) emission factors for traffic situations, (ii) aggregated emission factors for urban, rural and motorway driving and (iii) average-speed emission functions for situations where no detailed information is available on driving patterns. Average factors to address the effects on emissions of cold starting were based on observed trends and expert judgement. The effects of fuel properties on emissions were addressed in the model using the average results of the measurements conducted within ARTEMIS, and average adjustment factors were derived to address the effects of different types of inspection and maintenance on emissions.

Recommendations

The work conducted within ARTEMIS addressed a wide range of different topics relating to emissions from two-wheel vehicles. Nevertheless, a number of issues remain for future investigation, and some recommendations are given below.

At present, real-world driving data are limited to certain types of two-wheel vehicle and traffic situation. Real-world data should be recorded for a wider variety of vehicles to obtain more representative driving patterns for specific traffic situations.

Significant improvements have recently been achieved with regard to statistics for the European two-wheel vehicle fleet. Several sources are currently available on the internet, but the most detailed information can be obtained from ACEM. A detailed system of vehicle categorisation can be defined for in-use motorcycles. However, the more detailed the categorisation the more vehicles need to be measured to obtain emission robust factors. Therefore, it is recommended that the actual categorisation is adapted to the number of available emission results.

A detailed measurement protocol - which defines the measurement procedure - and a standard test report template are vital for assuring comparability of measurements carried out by different laboratories. The presence of a ‘test witness’ who is aware of the measurement procedure and preparative actions, bag analysis and data processing could improve the quality and comparability of the results. It is recommended that test drivers become acquainted with the test cycle and the specific behaviour of the two-wheel vehicle to be tested. It proved difficult to obtain motorcycles from private users for the main measurement programme. Dealers, rental companies and importers proved to be more co-operative. Two-wheel vehicles obtained from dealers, rental companies and importers are, however, generally well maintained and relatively new. Such vehicles are not recommended when addressing topics such as tampering or deterioration.

For certain vehicle categories, additional measurements are required to obtain an indication of cold-start emissions. The data obtained from the main measurement programme of ARTEMIS provide a solid basis, but should be extended to address the effects for vehicle classes for which few results are available (small two-wheel vehicles and vehicles that comply with Euro II and Euro III emission limits).

A dedicated measurement programme should be developed to further address the effects of fuel properties. The measurement programme should begin by evaluating the fuels that are on the European market. From this assessment, fuels should be selected that are different with regard to specific parameters, and emission tests should be conducted.

In order to obtain a more detailed understanding of this the effects of inspection and maintenance, a dedicated test programme should be conducted. The programme should involve measurements before and after maintenance on a significant number of motorcycles. In addition, a distinction might be made between vehicle categories and types of maintenance. Another issue of importance might be deterioration of the vehicle (effect of mileage on emissions).

Ideally, an emission modelling methodology should be developed before actual emission measurements take place in order to provide the necessary input data. The methodology applied within HBEFA and the ARTEMIS emission model is based on on-line and bag emission results. Further on-line measurements would improve the output of the emission model significantly. In addition, bag results for short test cycles would provide additional information for validation.

For a number of vehicle categories and traffic situations, the ‘representative’ driving pattern was based on data recorded for another vehicle category or traffic situation. Additional real-world measurements would improve the output of the emission model for these vehicle categories.

Due to the lack of emission data for current and future emission categories (Stage 2 and Stage 3), the output of the emission model will improve significantly when both on-line and bag emission measurements are conducted on vehicles compliant with the legislation.

H2.6 Cold start emissions (passenger cars)

Summary

Prior to ARTEMIS, three main methods were available in Europe for modelling cold-start emissions:

- HBEFA, used mainly in Germany and Switzerland (Keller *et al.*, 1995).
- The MEET approach (Joumard and Serié, 1999; European Commission, 1999).
- The COPERT III approach (Ntziachristos and Samaras, 2000).

Such models are necessary for large-scale applications such as national inventories, but could also be used for smaller scale applications. The geographical and temporal boundaries of the application depend upon the quality of the available data. One of the tasks of ARTEMIS was to develop an improved empirical model for cold-start excess emissions from passenger cars, including parameters such as the pollutant, the vehicle type and the driving conditions, and using all the existing data in Europe. The modelling of excess emissions under cold-start conditions for passenger cars was achieved using data provided by various European research organisations. Cold-start measurements collected during the MEET project, after MEET, and specifically for ARTEMIS were used.

Three models were developed, taking into account average speed, ambient temperature and travelled distance, amongst other parameters. The models were based on measurements made over four driving cycles at different ambient temperatures. The average speeds of these cycles ranged from 18.7 km/h to 41.5 km/h, and the temperatures ranged from -20 °C to 28 °C. In the first model the cold-start excess emission was expressed in grammes per start for a given pollutant and vehicle technology. The general formula was written in the form of a reference excess emission multiplied by functions depending on average speed, ambient temperature, travelled distance and parking duration. A second model was developed to assess the excess emissions from traffic. This second model requires extensive driving behaviour statistics, and is therefore very complex, but it allows the experienced user to modify the input data in order to model very specific situations. A third (simplified) model was derived from the second model, and this provides a unit excess emission (in g/km) for average European conditions. It takes into account the average speed, the ambient temperature, the hour of the day and the season.

The three models are available for numerous vehicle technologies (fuel and emission standard) covering the European situation, and for regulated as unregulated pollutants. The models can be applied at different geographic scales - at a macroscopic scale (national inventories) using road traffic indicators and temperature statistics, or at a microscopic scale for vehicles and trips. Where a model user does not have access to the necessary statistics, it is recommended that the most aggregated model (*i.e.* the third model) is used.

Recommendations

All three ARTEMIS models are improved versions of the former MEET model. The third model should replace the existing COPERT III cold-start model. In the future, the models could be improved in the following ways:

- By updating the models using new data when available, either for the most recent passenger cars, light commercial vehicles or heavy-duty vehicles.
- It would be much more precise to have cross-distributions for different speeds and ambient temperatures.
- The amount of supporting data has to be increased, especially for different speeds, lower and higher temperatures, and unregulated pollutants.

H2.7 Evaporative emissions

Summary

The ARTEMIS model was the first update of a European model for evaporative emission factors since 1993. The following mechanisms of evaporation were considered: (i) real time diurnal emissions (sum of diurnal emissions and resting losses), (ii) hot-soak emissions and (iii) running losses. The aim was to review existing emission factor models and to perform measurements to fill some of the main gaps. Following this work, the most suitable model approaches were selected and, where possible, the model parameters were adapted to the results of the measurements. From the literature review and the measurements, it was possible to cover the following categories of petrol vehicle:

- Cars - pre-Euro I
- Cars - Euro I and II
- Cars - Euro III and IV
- Cars - Euro I to Euro IV with failures in the fuel system (leakages)
- Motorcycles (>50 cc cylinder capacity)
- Mopeds (<50 cc cylinder capacity)

New measurements were only conducted for the category ‘Cars - Euro III and Euro IV cars without failures in the fuel system’, for which no emission factors were previously available in Europe. However, only three cars were tested in ARTEMIS, and this was much too small a sample to be representative of Europe. Thus, the ARTEMIS model made use of data from extensive measurement programmes conducted in the US. The MOBILE 6 method is suggested for simulating hot-soak and diurnal emissions. The ARTEMIS vehicles were therefore measured over the standard European and US test programmes, with different temperature cycles. The USEPA data were considered to be representative of European vehicles where the corresponding vehicle categories are selected (controlled carbon canisters were introduced in the US much earlier than in Europe). Due to different type approval tests in EU and US, the data from USEPA included in the ARTEMIS model may result in an underestimation for hot cycles and for parking durations longer than 24 hours, as the carbon canisters in European cars are, on average, smaller than those in US. However, no corresponding data on the fleet and no data on the numbers of vehicles parked for multiple days are available. Also, the rate of cars with failures in the fuel system was gained from US field tests, since there are no data for Europe. Running losses should be calculated based on a modification of the CORINAIR methodology. Data for light goods vehicles were not available, and therefore the formulae for passenger cars are used for this category. Hydrocarbon emissions from the manipulation of fuel during refilling are not included in the model.

The results from the model showed that evaporative emissions from Euro III and IV cars are substantially lower than those from Euro I and II cars, although emission factors for Euro III and Euro IV seemed to be higher than those predicted by older models (e.g. COPERT). The more stringent emission legislation and more advanced test procedures have led to the introduction of more sophisticated and durable technologies, which are monitored by on-board diagnostic systems. The main remaining sources of evaporative emissions from road traffic are therefore old cars and two-wheeler vehicles without a carbon canister and newer cars with failures in the fuel system.

The measurements showed a good performance for Euro III cars for all test cycles. Only a car with a small carbon canister showed a clear increase in evaporative emissions when the temperature and/or the test duration was longer than defined in the European type approval procedure.

Compared with the existing European models, a category of 'vehicles with failures' was newly introduced, although no data on their share in the European fleet is available. Since there is no indication that the European vehicles may have fewer failures than the US fleet, the rates of failures found in USEPA field tests are assumed for Europe. All the available measurements on European vehicles were performed on quite new cars with low mileages driven. Thus no 'high emitters' were included in the European data set, yet. The approach with 'vehicles with failures' is open to include future research on this topic. Such a research programme on the conditions of the fuel systems of older European cars would be very important if more accurate emission factors are needed for evaporative emissions of vehicles in the future.

As described, the shares of vehicles with failures are only based on assumptions. The introduction of failure rates for the vehicles as well as the different model approaches lead to evaporative emission levels which are higher than those provided by the European COPERT model. For typical driving of a vehicle on a summer day, the new ARTEMIS model gives approx. 145% higher evaporative emissions for the average pre-Euro I car, +360% for the Euro I and II cars and +80% for Euro III and IV cars than compared to the COPERT approach.

Recommendations

There is clearly a need for further measurements on evaporative emissions from European vehicles. Previous models did not include measurements conducted within the last decade, and the ARTEMIS model is only based on tests on three cars measured. The current database is much too small to establish a reliable model for evaporative emissions, and to allow an estimation of uncertainties to be made. Data for light commercial vehicles are also required, and if HC continue to be relevant, more tests over real-world temperature cycles would be advantageous.

H2.8 Validation

Summary

In the ARTEMIS validation exercise for road transport, measurement campaigns were performed in three different European tunnels: the Lundby tunnel in Gothenburg, the Plabutsch tunnel in Graz, and the Kingsway tunnel in Liverpool. The three tunnels differed in terms of their gradient, vehicle fleet composition, traffic volume, and traffic speed. The main aim of the work was to determine real-world emission factors for various gaseous pollutants and PM for the whole vehicle fleet, as well as for LDVs and HDVs. The tunnel-derived emission factors were then compared with those in the ARTEMIS emission model and with national emission factors used at the time the tunnel studies were carried out.

In all three tunnel studies there was a good agreement between the measured CO_2 emission factors and the emissions derived from calculations using ARTEMIS emission factors. For the Lundby tunnel, the CO emission calculated with ARTEMIS model was much higher (60-70%) than the measured emission, and the NO_x emission calculated with ARTEMIS model was slightly lower than the measured emission factor. In the Plabutsch and the Kingsway tunnel studies, the opposite results were obtained. However, the Lundby tunnel study mainly delivered emission factors for a strong downgrade (-3.5%), and is not really comparable with the Plabutsch and the Kingsway tunnel studies.

It could be concluded that the ARTEMIS CO emission factors for LDVs appear to be much too high, whereas the emission factor for NO_x and HDV is slightly too low, although much better than the emission factors formerly used in emission models.

Recommendations

- NO_x emissions are strongly dependent upon the vehicle load. Therefore, it is very difficult to calculate HDV emission for a specific traffic situation without knowledge of this important parameter. The CO emission factors for LDVs should be revisited, as the emission model HBEFA 1.2A (used until 2003) showed a much better agreement with the measurements than the new ARTEMIS database.
- Tunnel studies have proven extremely powerful environments for the validation of road transport emission factors. The ARTEMIS project clearly demonstrates the validity of this technique, and also highlighted the cost benefits over existing emission measurement techniques.
- Where tunnel studies are to be employed, it is vital that individual vehicle characteristics are recorded, and that the road link has significant changes in traffic composition during the monitoring period. The Sunday HGV bans operating in the Plabutsch tunnel clearly so the benefits of this parameter on the derivation of emission factors.
- Remote sensing of vehicle emissions were also incorporated within the validation programme, and provided robust results on emission distributions. The future use of remote sensing technologies should be considered.

H3 Rail transport

Summary

In ARTEMIS, a model was been constructed for estimating energy consumption and emissions from rail traffic. Using the model, calculations can be made on the basis of knowledge of a distribution of operational characteristics with respect to either time or distance. The model was evaluated on 18 passenger train routes and 12 goods train routes, and the results were compared with emissions calculated on the basis of measured engine power and energy consumption.

For passenger trains, the model was able to calculate energy consumption to within 15%. For goods trains, the variation was slightly higher. NO_x emissions could be estimated to a similar level of accuracy using average emissions factors applied to the total energy consumption. and not individual operation points. Emissions of CO, HC and particulate matter were more sensitive to individual operation conditions and specific engines, and could be estimated to within 25-30 % using average emissions factors.
It was concluded that the concept of dividing operating patterns into a speed acceleration matrix and calculation energy consumption from train data and estimates of rolling resistance parameters was a viable approach. The emissions calculation included technical factors in a correct, but not in an overly complicated manner. It is possible to apply the model to a wide range of fleets, from a single run to a national average for a train type. The requirement is that a reasonable estimate of the temporal or spatial distribution of the operating condition of the type of train analysed is known.

One possibility for obtaining data is the use of timetables. In this case, distances are either known or readily available, and travel times directly given. With standard corrections for acceleration/deceleration times or distances, operating statistics are readily available for almost any passenger route for schedule traffic. Goods traffic travel data is not generally available in this form, though some typical operations are shown in the report.

Recommendations

- The use of black box train trip outputs proved a valuable source of data. These data were restricted to examples provided by the Danish DSB. It is therefore recommended that efforts are made to gain access to these data from other train operators, covering a variety of locomotive and route types.
- The effect of aerodynamics on energy consumption was investigated, and it was evident that significant energy consumption disbenefits were associated with mixed freight services. The covering and stream lining of the individual wagons and the train-wagon configurations result in significant energy consumption savings. The make-up of trains, and its effect on energy consumption requires further analysis.
- Only conventional diesel fuels (plus electric) were examined as part of this work. The growth of alternative fuels, and the early introduction of biofuels into locomotives requires further evaluation.
- Further work is required to characterise the introduction of new rolling stock, across the EU.
- The analysis of electric locomotive emissions requires an on-going assessment of EU energy policy and power generational mix.
- The geographic allocation of electric locomotive emissions requires further discussion, particularly where the route passes over regional or national boundaries.
- The ARTEMIS rail model has proven to be significantly more robust than the earlier MEET model. It is therefore recommended for use within impact assessments and inventory developments.

H4 Inland shipping

Summary

In the ARTEMIS work on inland shipping, nine ship classes were established, based on a vessel's size and the waterways it is able to navigate. A technical model, which had previously been partially developed by DTU, was improved and validated using experimental data. Special focus was put on the specific fuel consumption of engines used on inland shipping vessels, as this was an area of considerable uncertainty, and a correlation was developed to provide specific fuel consumption values according to the engine output. The model developed for inland shipping in ARTEMIS is already in use for the TREMOVE project.

The input parameters required by the user include average waterway width, depth and speed limits, the share of different vessels on the waterway, and their average load. As the model is intended for non-expert users there is a provision for most of the parameters to be set to default values.

The model was validated for a wide variety of service conditions using full-scale tests and towing-tank tests. The validation showed that the model results correlated well, on average, with experimental data. The accuracy of the predicted engine output against measured values was between 80% and 107%, with the deviation ranging from 19% to 30%. The model performance was therefore deemed acceptable for the purpose of ARTEMIS, which is to provide average indicators for the entire fleet and not precise values for single vessels. Thus, it operates on very little input data, with a trade-off in accuracy being inevitable. As long as the limits and guidelines for the input parameters are observed, the model presented should provide a reasonable estimate of the operation of an average vessel of the type and size in question under the given service conditions.

The ARTEMIS model was subsequently been put to use to provide examples of indicators that may be produced for typical vessels in service under different conditions. These calculations gave an idea of how the different parameters (speed, draught, waterway depth, *etc*.) influence the energy consumption of inland vessels. The results were calculated for arbitrary conditions, and did not refer to specific waterways.

The sulphur content of marine gas oil used on the inland waterways is to be further reduced to 0.1% by mass from 1 January 2008. The effects of this measure can be incorporated in the ARTEMIS model by means of changing the emission factors used. The reduction of fuel sulphur is also likely to influence PM emission favourably, and the TRENDS model can be used to predict these reductions. For PM, the effect of other standards that may be introduced in the meantime are not taken into account. Proposed Stage III/IV emission standards for non-road engines have been published by the European Commission. It is not possible to predict the effect of these measures without more information on their implementation and on the replacement rates for engines in the fleet. However, the long working lives of ship engines means that the regulations will not have any considerable effect on emission levels for another couple of decades.

Connections between the ARTEMIS inland model and the GISCO information on navigable waterways of Western Europe was examined. However, due to the lack of detailed representation of the inland waterway network and traffic in the GISCO database no linkage was possible. Applications are still possible on a local scale, by retrieving waterway information from regional monitoring organisations which record the water level on different waterways over the year. As this information is not processed and organised in a database that can be connected to ARTEMIS, this requires considerable time and effort. The development of River Information Services (RIS) is likely to provide a good source of information on waterway characteristics, and it is hoped that the data necessary to also connect emission calculations to GIS will be easier to obtain in the future.

Recommendations

With the relevant information available, a detailed profile of the energy economy of transport by inland waterways can be obtained, with reference to different routes or types of goods. This would require better knowledge of both waterway characteristics and traffic statistics. The following are aspects need be investigated further:

- Average waterway, width, depth and speed regulations.
- Number of days per year a certain average depth is maintained per waterway.
- Share of each vessel type that operates on a given waterway.
- Average speeds for upstream and downstream navigation for a given vessel type.
- Average load factors for upstream and downstream navigation for a given vessel type.
- Number of locks and average time for lock passage per route

Information on some of the above points exists in the form of studies performed by local authorities, but statistics reported to EUROSTAT are not of such detail. Still if there is specific interest for a route or type of cargo the model results should provide an easy way to evaluate transport choices involving inland shipping.

Any likely changes in ship emissions due to fuel sulphur content or emission legislation will need to be taken into account in the ARTEMIS model via changes in the emission factors.

Further examination is required of the connections between the ARTEMIS inland model, the GISCO database, the information from regional monitoring organisations, and River Information Services.

H5 Maritime shipping

Summary

The quantification of emissions from maritime shipping is still in its initial stages. In the ARTEMIS maritime shipping report, a large amount of information was given for calculating ship emissions under all normal states of operation, and this information has been summarised here. The maritime shipping report also presented emission factors to be applied to ships fitted with emission-control equipment, as well as a variety of information that can be useful depending on the type of assessment that is of interest. The intention was to produce an accurate estimate of emissions, based on information that is normally presented when ships call ports.

The ARTEMIS methods (one simple and one detailed) are based upon typical service speeds and main engine power for ships of given types. As individual ships are unique, have a certain service speed, a certain load condition, and travel in a range of weather conditions. Each of these factors can affect the power requirement, and there will always be some uncertainty in the emission factors in relation to such specific applications.

Recommendations

The following recommendations were made with respect to maritime shipping:

- Useful, stable and reliable activity data are required. The current standard is not acceptable for some types of application, such as the evaluation of trends and development in maritime shipping emissions.
- Article 4 of Commission Decision 2001/423/EC states that 'the highest level of detail in which (statistical) data may be published or disseminated is the level of port to and from maritime coastal area'. This effectively means that these data cannot used assessments at the level of detail demanded by the Commission.
- At present, the most technically sophisticated, inclusive and reliable source of activity data is the AIS. Continuous information on a ship's speed, position and heading, as well as weather conditions will make it possible to estimate the power used and the ship's fuel consumption. The logging of exact routes of will also allow emissions to be assessed in specific sensitive areas. However, the main increase in the quality of predictions will come from the improved reliability of shipping movements and vessel identity.
- Emission factors must still to be added to existing databases as external information.
- The ARTEMIS model provides two main approaches for determining the fuel consumption and emissions for a particular vessel type. The first approach - the 'simple method' - involves the use of the ship's type and size to look up emission values in a static table. The second approach - the 'detailed method' – can be used if more information is available, and also involves average speed, the main engine power output and the main engine type. Two further considerations apply: emissions associated with the effects of auxiliary engines in port, and the effects of emission-control equipment.
- The model provides emission factors for 'typical' vessels and conditions For more thorough assessments a more accurate result is only achieved by going into a register to obtain more exact information of the individual ship, such as, fuel consumption at service speed and type of engine and to obtain the quality of fuel used from the ship.
- When restrictions are introduced on emissions, the accuracy in the emissions will become higher as control systems will give emissions limits. These limits have to be monitored in some way. Having such monitoring system will assist the engineers of the vessels to tune in the engines. It will thus not be a function of the condition of the engine or how the chief engineer of the ship tunes the engine that determines the emissions.
- The outlook for the near future is very positive, and systems will soon be available that can assess emissions automatically without violating the integrity of ship operators or ports.
- Following the entry into force of Annex VI of MARPOL, several Member States submitted a request to the International Maritime Organisation (IMO) for changes to the ship emissions standards. These proposals will be discussed in due course and will need to be fully justified if they are to be adopted by the IMO. Moreover, the Council of Ministers has concluded that the Community should adopt its own measures to reduce NO_x emissions from EU-flagged ships if progress is not forthcoming at the IMO. Given this, it is likely that there will be a requirement to analyse in more detail possible measures to reduce atmospheric emissions from maritime sources.

H6 Air transport

Summary

The ARTEMIS programme evaluated data from the ICAO emission database and supplemented and compared these data with new in-service measurements from Frankfurt-Main, Vienna-Schwechat, London Heathrow and Wroclaw airport. Results of these measurements indicated that in-service emissions are different from emission measured over standard conditions. This can result in significantly different results in emission calculations.

Emissions from engine start are not included in the conventional LTO cycle modelling, but have a significant influence on total emissions and local air quality around airports. In the first step of this task a common methodology was developed to measure a range of exhaust pollutants using FTIR and DOAS equipment. The work incorporated IFU's experience in air traffic emission measurements and involvement and interaction with other projects, such as AEROCERT and AEROJET. Both of these projects dealt with the improvement of measurement techniques. Improved non-intrusive measurement methods such as FTIR developed in AEROJET 2, were employed and further developed. To validate the whole system, intrusive measurements and engine test bed measurements were also undertaken.

Based on explorative measurements at Frankfurt and Heathrow airport, enhanced measurements were made at Vienna and a second campaign at Heathrow Airport. The main objective of these measurements was to test the data collection procedure in relation to the operational requirements of the airports. The calibration of the measurement procedure was achieved through the use of a series of measurements undertaken on a burner unit, used to simulate an exhaust jet plume. A second explorative measurement campaign was undertaken in Aachen, Germany on a real aircraft engine.

The ARTEMIS programme may thus be considered one of the first steps towards the development of real world aircraft exhaust emission measurements, including significant measurements on APUs. Unfortunately, due to a lack of data from the aircraft operators on specific power settings during measurement campaigns, these data were not fully used for the generation of the emission estimation methodology.

Finally, the ARTEMIS aircraft work used the TRENDS air traffic methodology and database as the basic modelling platform. The ARTEMIS work may thus be seen as an extension to this pre-existing tool. The work focussed on the 40 most relevant aircraft/engine combinations used in Europe, representing about 85% of European instrumented flight rules (IFR) flights. The project extends basic knowledge on NO_X, CO and HC species, and allowed the inclusion of preliminary measurements on species such as methane, particulate matter and NO_2 within the aircraft emission database. Significant measurements on APUs were undertaken and incorporated within the TRENDS database model.

Finally the TRENDS model was extended to include some insight into emissions and fuel consumption associated with the newest aircraft technologies and changes in the fleet mix. This will allow improvements in the use of the TRENDS model for the estimation of future emissions and to allow the assessment of transport scenarios and policies over a 20 year time frame.

Recommendations

- Throughout the ARTEMIS project, existing measurements and databases for in-flight emissions arising from the European Commission aeronautic research projects proved difficult to access. The European Community Shared Environmental Information System (SEIS), designed to allow and facilitate the European dissemination of relevant environmental data and the INSPIRE Directive (2007/2/EC) which came into force during May 2007, should be used to promote the generation of European exhaust emission databases.
- The ARTEMIS project successfully measured a large number of APUs, and has thus assisted in in-filling this knowledge gap. These data have subsequently been used to develop a module for inclusion in the existing TRENDS aircraft emission methodology. Further development and validation of this module is required.
- Data on the use of APUs at specific airports, and for specific aircraft and airlines, requires collection. In addition, the trend towards the provision of electrical supplies and conditioned air provided from the stand, requires investigation.
- The ARTEMIS project did not develop a specific aircraft model. However, the need for a multimodal tool, incorporating aviation remains a requirement for the modelling community.
- The use of FTIR and DOAS in the measurement of LTO aircraft emissions has proven successful within the ARTEMIS programme. The on-going development of these techniques is recommended.
- Further work is required to assess the effect of ambient conditions (summer/winter, dry/wet) for different engine ages and maintenance (new/old, before/after overhaul) levels, for engine start up and different power settings (LTO cycle).
- Further work is required in the examination of emissions from new and proposed aircraft models, engine types, and fuels.

H7 Inventory model

Summary and recommendations

In ARTEMIS, the emission models for the various transport modes were converted into computer programs. The level of software development varied considerably according to the transport mode. By far the most detailed software package was produced for road transport. In the case of road transport a new generation of traffic situation modelling tools have been developed. However, given that the majority of the modelling community currently use average-speed based models, the basic average speed approach has also been retained. Finally, the growth in engine management and data interrogation techniques using CAN interfaces *etc*, has allowed the development of engine emission maps, which provide the backbone to the development of instantaneous emission models.

Less sophisticated packages were produced for rail transport, air transport and shipping, which ranged from Excel-based worksheets to a series of look-up tables, and proposed supplementary modules to existing modelling tools, respectively. Full details are given earlier in this report, and within the associated ARTEMIS project deliverables.

The development of a true multimodal transport emission model remains a future requirement. However, the basic transport mode tools developed within the ARTEMIS programme remain state-of-the-art, but further work on model integration is required.

Furthermore, as with any new database or modeling tool development, the ARTEMIS models require validation and verification, and comparison with existing inventory tools. Initial attempts at this validation process have been undertaken through modelling uncertainty analysis, and its use and intercomparison within the Swedish national emission reporting process. The requirement for further evaluations and enhancements remains.

H8 Developments following the completion of ARTEMIS

H8.1 Development of COPERT IV

One of the most important intended applications of the ARTEMIS work was the support of COPERT (see Section A3). In July 2007 a draft revision to the road transport Chapter of the EMEP/CORINAIR Emission Inventory Guidebook was produced, with the updated sections being summarised by Ntziachristos *et al*. (2007). Large parts of the methodology were drawn from ARTEMIS, and it was also proposed that the ARTEMIS methodology should be used in COPERT IV.

H8.2 EUCAR/JRC/CONCAWE research programme on evaporative emissions

CONCAWE, EUCAR and the Joint Research Centre of the European Commission jointly carried out a major test programme specifically designed to investigate the influence of petrol vapour pressure and ethanol content on evaporative emissions from modern passenger cars, as determined using the current European regulatory test procedure. The results of the experimental work have recently been published (Martini *et al*., 2007). Although the work has provide a large amount of new information on evaporative emissions, no new model for use in inventories was developed. However, Ntziachristos *et al*. (2007) also described a revised methodology for inclusion in the ‘Gasoline Evaporation from Vehicles’ Chapter of the EMEP/CORINAIR Emission Inventory Guidebook and COPERT IV.

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ARTEMIS: Assessment and Reliability of Transport Emission Models and Inventory Systems – final report

This Report presents the findings of the European Commission fifth framework project, ARTEMIS (**A**ssessment and **R**eliability of **T**ransport **E**mission **M**odels and **I**nventory **S**ystems) and describes the resulting inventory model. The ARTEMIS programme built upon the earlier recommendations arising from the fourth framework project MEET and Cost Action 319. It provides a summary of the research investigations undertaken within the ARTEMIS programme, and includes links where appropriate, to interactions with COST Actions (particularly COST Action 346) and national emission measurement and modelling programmes. The ARTEMIS project commenced in 2000, and had two principal objectives. The first of these was to gain, through a programme of basic research, a better understanding of the causes of the differences in model predictions, and thus to address the uncertainties in emission modelling. The project included a large emission measurement programme, designed to provide a significant extension to the available databases. For road transport, measurements conducted in many laboratories around Europe were used to examine the reasons for variability in the data, and to form the basis of a 'best practice' guide for future measurements. The second principal objective was to develop a harmonised methodology for estimating emissions from all transport modes at the national and international levels.

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