Annual Research Review 2009
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In times of economic uncertainty, and in the context of tightening medium-term public spending budgets, it is important to find effective, lasting solutions to transport issues that are supported by good evidence and understanding, and which can be implemented efficiently and cost-effectively. There is a continuing need to develop the evidence base to facilitate good decision making.

The economic climate has, of course, had some impact on travel behaviour, but as the economy begins to grow again the underlying trends will tend to reassert themselves: economic growth requires mobility of goods, services and labour, while personal economic growth drives aspiration for car ownership, mobility and accessibility. Globalisation and population growth add to these effects.

Policies to mitigate transport’s impacts on climate change have yet to impact significantly but nevertheless, in the medium and longer term, addressing transport’s contribution to environmental impacts will be essential. It is therefore important that appropriate policies are formulated and implemented now to reap the rewards downstream. Technological advances will assist in meeting the targets: smarter materials for vehicles – lighter vehicles and lighter engines – mean less fuel use and reduced impact on the infrastructure; new engine designs and fuel types can help significantly reduce the amount of greenhouse gases and air pollutants per driven distance. Technology can also help provide the information that enables better planning and execution of journeys or eliminate their need altogether.

Other factors also influence travel. The price of fuel clearly has a direct effect, but, as recent fluctuations in fuel price have shown, travellers are quite insensitive to such changes, at least at the scale at which they currently occur. The patterns of homes, workplaces, jobs and where people live and work influence where, and how, people travel. There are changes in demographies and lifestyle which influence, and are influenced by, mobility and the opportunities it affords. The proportion of elderly people is growing; retired people now have higher savings, living standards and life expectation, and therefore greater interest and opportunity in leisure and tourism.

At the end of last year, the Government published Delivering a sustainable transport system, a document that sets out the requirement for a sustainable transport system with its underlying aims and objectives, and the challenges that need to be addressed. It focuses on the challenge of delivering strong economic growth while at the same time reducing greenhouse gas emissions, and sets shorter term action on immediate problems while also contributing to addressing longer term challenges. This year, the Government also published its carbon reductions strategy for transport, setting out the tasks needed from the transport sector to contribute to the 2022 and 2050 carbon targets. As the strategy indicates, the consequence is that by 2050 our transport system will have to look fundamentally different. Both of these documents emphasise the need for problem solving to be conducted in a holistic way, so that policies and interventions mutually support the stated aims and objectives. Our activities at TRL reflect these realities, with work increasingly being multi-modal and multidisciplinary in order to provide effective solutions for our clients.

An example of the kind of new thinking that is required at a European level comes in the Forum of European National Highway Research Laboratories’ (FEHRL) Forever Open Road initiative, which TRL has helped create and drive forward. This meets the challenge of developing a truly inspiring vision for how roads will be built and maintained in the 21st century, setting out a revolutionary concept that brings together the best of what we have today with the best of what is to come in order to produce a road that is adaptable, automated and climate change resilient. Such practical visions, with the frameworks they provide and with the accompanying pathways for action, are essential if we are to deliver a transport system that meets all our future needs. They ensure that research and development are conducted as part of a coherent strategy in support of clear aims and objectives. Research, and the knowledge it provides, is thus best able to serve policy formation and implementation.

Dr Susan M Sharland
Chief Executive
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Introduction
Neil Paulley, Director of TRL Academy

The benefits provided by an efficient multi-modal transport system are very large, adding greatly to societies' wealth and prosperity. However, set against these benefits are the high costs of developing, operating and maintaining our transport system, coupled with the large social and financial costs associated with transport externalities such as road accidents and environmental impact. These are complex issues which are often deeply interactive. An improvement in one area can often lead to a negative effect in another. It is often no longer possible to deal with a particular transport issue in isolation and a much broader assessment of many, often conflicting, issues may well be needed when searching for the most appropriate solution. You will see that in our review of our work this year we have included many examples that reflect the broader based approach to transport research that is now required.

Our work in the field of transportation is such an example. This is primarily concerned with how we move people and goods from one place to another, but research conducted in this area increasingly requires a multidisciplinary approach, embracing many different specialist skills. These include engineering, telecommunications, software and computing skills, vehicle manufacturing, behavioural issues and human factors.

The environment is another area requiring a multifaceted approach to problem solving, where often reductions in environmental impact impose additional costs on a proposed change or imply a negative impact on travel. Combating climate change and minimising the production of greenhouse gases are major challenges facing society today. The UK Government has set stringent targets for the reduction of greenhouse gases, and transport has a key role to play in achieving the targets set. These reductions will require not only technological improvements to vehicles and construction processes but also a fundamental change in the travel behaviours of individuals. The policies required to bring about these changes will need to be based on a good understanding of the broader issues, and our research must be able to provide this.

The transport infrastructure provides the foundation for an efficient transport system, and our work on this topic has continued to support the work of the Highways Agency – in particular to provide more durable, safer, environmentally sustainable roads and structures, and better ways of maintaining the network. During 2009, we established a Ground Engineering Centre of Excellence at our offices in Edinburgh, which will provide a focus for our activities in ground engineering and will embrace both traditional and newer environmental and sustainability activities.

Our work on road and vehicle safety covers a broad spectrum of research and consultancy. Some activities concentrate on how to influence the attitudes, knowledge, skills and behaviours of road users; others analyse accident statistics to help set casualty reduction targets, monitor progress, assess the effectiveness of safety interventions and investigate trends – in particular types of accident, so that these can be tackled. In the field of vehicle safety, we develop an understanding of vehicle crashworthiness and occupant and pedestrian protection, and incorporate this knowledge into test procedures for use by the Government and consumer testing bodies. The research is supported by several large-scale facilities, including a test track, impact test facilities and both car and HGV driving simulators.

While TRL’s core business continues to be the creation of knowledge and its use in finding solutions to our customers’ problems, we are very much aware that the research process itself has helped us to generate a wide range of unique, state-of-the-art facilities. Apart from the various research applications that these facilities support, they can also be used, along with our in-house technical expertise, to provide a more routine and repetitive function in carrying out standard testing and certification of products and processes. During the course of the year, we have seen a substantial growth in this aspect of our work, which has been led by the launch in the latter half of 2008 of a subsidiary company that provides a range of independent, third-party certification and assurance services to our customers. To reflect this part of our business, we have in this year’s Review included a section describing some of the professional consultancy services that we currently offer.

In addition, the Review highlights a few of our many scientific achievements, followed by a small collection of papers that illustrate some of the work in which we are involved. The Review concludes with a full list of publications demonstrating the depth and breadth of our interest and capability.
Research highlights
During the course of the year, TRL undertakes and completes several hundred projects for its clients. As might be expected from the nature of the work, these projects are extremely varied. They range from those that are long term – perhaps forming part of a comprehensive programme of study, and where the output would be expected to have a broad application – to those that are more directly related to the solution of a specific problem, and which can be completed in a relatively short timeframe.

Given the diverse nature of this work, it is not possible in a review to encompass all that TRL does. However, in order to provide a reasonable overview of our activities, the following sections highlight a selection of our main activities and achievements during 2009. Although there are clear overlaps between the various subject areas of our work, we have organised our “Research highlights” under four general application areas. These are listed as “Infrastructure”, “Road and vehicle safety”, “Environment and sustainability” and “Transportation”. Some of the work we do in developing links with other professional institutions, and our involvement in training and education, is also included in this part of the Review.
This review of infrastructure research during 2009 includes research to support the Highways Agency in reducing congestion and improving journey time reliability through its Managed Motorways initiative. Another key element of our research this year has been the development of a carbon-accounting tool to assess the impact of producing and laying asphalt and asphalt-related products.

We have also taken the lead in developing the concepts for the "5th generation road – the Forever Open Road". This is being done in collaboration with our European partners in the Forum of European National Highway Research Laboratories (FEHRL), and is developing both the concept for the road of the future and the research needed to deliver it.

A more detailed description of some of our key research areas is given below.

**MANAGED MOTORWAYS**
We have undertaken research to support the implementation of the Government’s plan to increase hard shoulder running (HSR) to improve the UK’s road network. HSR, the controlled use of the hard shoulder during times of heavy congestion or during incident management, is part of the Managed Motorways initiative. This is a “tool-box”, which facilitates the dynamic control of traffic for congestion and incident management.

Previous work has shown that the structural condition of motorway hard shoulders is generally unknown and that accurate construction information is not generally available. Furthermore, prior to 1980 there was no requirement for the hard shoulder to be built to the same standard as the main running lanes and it is therefore possible that a proportion of the hard shoulders considered for HSR may require strengthening in order to carry the anticipated future traffic.

Our research has focused on the application of the Traffic Speed Deflectometer (TSD) to rapidly assess the condition of hard shoulders. The TSD is an articulated truck which is owned by the Highways Agency but is operated and maintained by TRL[21, 22]. It measures pavement deflection (road strength) under the nearside wheelpath of the vehicle, using laser technology. The derived measurements are dependent on the survey speed of the vehicle. It has been developed to be a future traffic-speed network survey tool, and results to date have been validated only for surveys when the vehicle is operated at a nominally constant speed within the range of 60–80 kph (40–50 mph).

In order to evaluate the structural condition of the hard shoulder pavement, the TSD was used to measure both the general deflection of the hard shoulder and also the relative difference in deflection between the hard shoulder and the first running lane (Lane 1). Measurements were taken at the same target speed.
PAVEMENT CONSTRUCTION AND MAINTENANCE
Making surfacing safer and more sustainable
We are undertaking research for Transport Scotland to investigate how to make road surfaces safer and more sustainable. Based on emerging experience from both Germany and the UK, our research aims to improve the current specification for surfacing. Experience from Germany has shown that improved durability can be achieved through using a denser material made with smaller-sized stones and higher binder content that possess a lower surface texture.

Draft mixture specifications based on the German Specification for Stone Mastic Asphalt (SMA) and the new European Standard have been prepared, including a requirement that the surfacing be treated with grit. Eight SMA materials with different size aggregates were laid on the M8 between Edinburgh and Glasgow in November 2008. The surfacings were tested in November 2008 and again during 2009 to evaluate the potential of SMA using smaller aggregates, the effectiveness of treating the surface with grit and the texture and skidding performance.

Surface testing at various speeds includes Sensor-measured Texture Depth (SMTD) and road surface skidding resistance measured using a variety of test devices that include the measurement of sideway-force coefficient using the Sideway-force Coefficient Routine Investigation Machine (SCRIM), grip number using the grip tester, and locked-wheel skid number using the Pavement Friction Tester (PFT).

The outcome of this trial could see a major change in the way surface course materials are specified in Scotland.

Environmental credentials of the asphalt industry
We are undertaking a collaborative research programme for the Highways Agency, the Mineral Products Association (MPA) and the Refined Bitumen Association (RBA) to provide sustainable solutions for the asphalt industry. The outcome of this research should provide more options for surfacing materials and aggregate sizes, leading to more efficient use of premium-quality aggregates. The research will also lead to the development of a carbon-accounting tool for the asphalt industry. This will enable a uniform system to be used across the industry to assess the impact of producing and laying asphalt and asphalt-related products. A web-based calculation tool known as asPECT was launched in October 2009, which covers the acquisition of raw materials, transport, processing, road component production, transport to site, and laying and compaction (see also p. 29 of this Review). Further developments will include scheme-specific works, maintenance and “end-of-life” strategies. The tool will enable comparisons to be made between material and processes, and will highlight areas where reductions in CO₂ can be made.
Research highlights: Infrastructure

Development of best practice guidance for recycling road surfacing

Proprietary thin asphalt surfacing systems were first introduced in the UK in 1991. The need to recycle thin surfacing systems is more critical than with many other generic surfacing materials because of the quantity of relatively scarce aggregates with high skid-resistance properties within the layer. Our site trials have demonstrated comparable field performance over six years using recycled aggregates. The treatment of Reclaimed Asphalt (RA) and the quantity that can be added depend on the consistency of the RA source, compatibility with proposed new surfacing, asphalt plant capability and residual binder properties. Two major resurfacing schemes have been successfully constructed incorporating up to 25% of the existing surfacing into the new surface course layer. Laboratory investigations with RA sources containing different viscosity binder properties, and the results of performance measurements from the field, have led to the development of best practice guidance for future schemes. Further monitoring of some of the site trials is being taken forward in a European project investigating end-of-life strategies for asphalt pavements.

Reservoir pavements

Recent floods have provided a reminder of the dangers of the predicted 20–30% increase in rainfall as a result of climate change. Unfortunately, sealed paved areas prevent the natural dissipation of rainwater. Consequently, increases in rainfall and infrastructure developments will cause both the rate and volume of water run-off from built-up areas to increase unless mitigating actions are implemented. The Department for the Environment, Food and Rural Affairs (DEFRA) aims to maintain rainwater discharge rates at current levels.

One solution to this problem is the wider use of Sustainable Drainage Systems (SuDS), which deal with water run-off at source or discharge it by mimicking the natural processes of rainwater distribution to the air and the ground.

Relative effectiveness of thin surfacings

A major change in the surfacing materials being used on HA's roads has been the switch, since the mid-1990s, from the use of Hot Rolled Asphalt (HRA) to thin surfacings. The full effects of this change are being assessed by TRL in terms of whole-life costs, sustainability and environmental impact. The assessment is needed to steer and justify policy with regard to surfacing materials which will be used in the future.

Proprietary thin surfacing systems include paver-laid surfacing dressing, SMA, asphalt concrete micro-surfacings and surface dressing. The use of proprietary thin asphalt surfacing systems is permitted on trunk roads provided the system is approved. The approval is currently achieved under the Highway Authorities Product Approval System (HAPAS), run by the British Board of Agrément (BBA) on behalf of highway authorities including HA. Our research has demonstrated that paver-laid categories of thin surfacing achieve an average in excess of eight years service. The estimates still have to be extrapolated for the more durable categories, and the estimates of service life need to be more robust for all the categories. Our current research programme will provide this information, and the results will be published in 2010.
SuDS can be built into the road infrastructure in a variety of ways, including the innovative reservoir road pavement. These pavement structures include porous materials, which delay and reduce the rate of water run-off to outfall drains. Also, when water is allowed to infiltrate into the soil reservoir pavements reduce the total amount of water flowing to drains. These pavements have historically been constructed for lightly trafficked applications, but we are carrying out research for HA to develop guidelines for their use on more heavily trafficked roads. We are leading the project team, which also comprises Halcrow, Aggregate Industries, Tarmac, the Agriculture Development Advisory Service (ADAS) and the Centre for Ecology and Hydrology (CEH) in Wallingford.

Trial sections have been constructed, which have enabled us to examine the performance of sealed reservoirs that protect the underlying soil from softening by infiltrated water, as well as pavements on permeable soils that can drain water without significant weakening. Also trialled were pavements with porous asphalt surfaces, which reduce spray and are less complicated to build, and pavements with traditional asphalt surfaces that are more robust but require edge drains. Finally, pavements with brick pavers, which are more resistant to damage by fuel spillage, were constructed to represent service areas where vehicles park.

**Longitudinal grooves**

Concrete surfaces provide adequate levels of skid resistance and texture depth throughout the course of their life. However, when a concrete surface deteriorates, both its skid resistance and texture depth reduce. At present, the accepted maintenance options (detailed in the Design Manual for Roads and Bridges, HD36/06) tend to be expensive. We are researching the effectiveness of a new grooving technology, which produces longitudinal grooves while the machine moves down the carriageway (previous technologies produced transverse grooves). This new process is due to be trialled on the A12 Chelmsford bypass. Prior to this, an initial trial was carried out at Alconbury Airfield.
Footways

We are continuing to undertake research on footways. We are developing and testing a new footway survey, the Footway Network Survey (FNS), which was formerly referred to as the Coarse Network Survey (CNS). This work is funded by HA and Transport for London (TfL), and overseen by the Roads Board’s Footways and Cycletrack Management Group (FCMG). The FNS is intended to provide a cost-effective approach to footway surveys with the added option of collecting aesthetic data.

Currently, FCMG is working towards the implementation of FNS within the United Kingdom Pavement Management System (UKPMS) for a full roll-out aimed for the next financial year (April 2010). This is well under way, with the publication of Technical Notes that include:

- Technical Note 3 – Highway Maintenance Data Interchange Format (HMDIF) File Structures and Content
- Technical Note 48 – Introduction to Footway Network Survey

The FNS has also been incorporated within the updated Visual survey manual, surveyor training and accreditation and software accreditation.

We are also involved with other footway research for FCMG that includes reviewing the materials and methods used for the construction of footways and cycle tracks, and the factors affecting the slip resistance of footway and cycle track surfaces.

Further information about the FNS and the footways research undertaken for FCMG is available at www.footways.org.

Footway survey

Research highlights: Infrastructure

TECHNOLOGY DEVELOPMENT

Our work into enhancing the measurement of road markings has continued, with the delivery of a new survey vehicle to undertake surveys of the trunk road network. This survey vehicle has enabled us to implement the results of the research we previously carried out for HA. Following delivery of the equipment, we have undertaken further work to improve the reliability and repeatability of the measurements of the retro-reflectivity of road markings and road studs.

Continuing the theme of traffic-speed inspection, we have carried out work to enhance the ability to measure surface rutting. Traditional traffic-speed techniques of measuring rutting often rely on the interpretation of measurements of the transverse profile of the road surface collected using fixed lasers, such that each profile contains 20 to 30 points. In order to improve on the accuracy of measuring surface profile, we have employed a scanning-laser measurement system mounted on HA’s HARRIS2 survey vehicle. Further details of the HARRIS2 vehicle can be found on p. 52 of this Review.

This development offers the advantage of greatly reducing the influence of the position of the survey vehicle on the road, road markings and kerbs. When this new approach is implemented in future routine surveys, it is anticipated that the higher level of consistency will improve maintenance planning and also offer the ability to expose trends in deterioration – hence predicting future maintenance requirements.

We have continued with the assessment of novel techniques and the development of these into practical tools for use in highways maintenance. In particular, we have begun trials of the novel application of Light Detection And Ranging (LIDAR) as a traffic-speed measurement system. A scanning LIDAR system has been implemented on the HARRIS2 survey vehicle to collect detailed 3D measurements of the environment surrounding the survey vehicle as it is driven along. Software is being developed to capture the data, account for the motion of the vehicle (by integrating the equipment with HARRIS2’s on-board inertial measurement systems) and render the scans as a 3D image of the road and surrounding infrastructure. Further details of the LIDAR system can be found on p. 52 of this Review.

Road profile image produced by HARRIS2, showing presence of rutting
Brine-only treatments and pre-wetted salting with a uniformly graded salt are used in some countries and by some UK local authorities. Our research on these products has concluded that brine-only treatments are particularly effective for the treatment of whole routes in some areas, especially in low-humidity and low-temperature conditions. They were also recommended for top-up treatments for slip roads and the hard shoulders of Managed Motorways. HA has commissioned further research this winter to evaluate brine-only treatments in a series of performance trials.

Four years ago, TRL carried out a desktop study on de-icers suitable for the treatment of railway station platforms. It was concluded that rock salt is not suitable because it corrodes track circuits. Alternative de-icers were proposed for consideration along with those recommended by Network Rail. We have now started a follow-up study to review progress and to carry out tests on different de-icers to determine their effectiveness, their effect on the slipperiness of platform surfacing and the change in residual salt levels with time and footfall. A best practice guide is to be developed that details recommended de-icers, spread rates and treatment frequencies.
Research highlights: Infrastructure

ROAD LIGHTING
We are undertaking research to gather information from Transport Scotland and local authorities on the experience gained from their trials of solar and “intelligent” illuminated road studs. Illuminated road studs provide enhanced guidance for road users compared with retro-reflective lines and studs. Solar LED studs can provide good guidance at night, while mains-powered studs can also provide this function in bad daytime visibility. The latter can also be networked and remote controlled to provide road users with instructions, such as in implementing a tidal-flow system. Guidance is one of the functions of conventional street lighting which may be significant in maintaining road safety. It is possible therefore that illuminated studs may reduce or remove the need for full lighting, particularly in rural areas, with concomitant savings in energy costs and visual intrusion.

Some of our recent work on street lighting and safety issues can be found in the list at the end of this Review[36, 37, 38, 39].

STRUCTURES
Acoustic monitoring
We have a long history of research into the deterioration of post-tensioned concrete bridges. One of the outcomes of this research has been the validation of an acoustic monitoring system for detecting wire fractures. We have installed the monitoring system on a number of bridges where there is concern about the risk of corrosion and fracture of wires in the post-tensioned tendons. This is enabling the structures to remain in service. This not only extends their service life but allows additional time for remedial measures or replacement of the structure to be planned and budgeted. Further details of the monitoring work we are currently undertaking on concrete bridges can be found in the section on specialist consultancy services on p. 51 of this Review.
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The visit attracted considerable media interest and included appearances on Korean national television.

Amongst TRL’s many publications in 2009 was a major review report on Improving the stability of slopes using a spaced piling technique [1]. The report focuses on demonstrating how a single row of bored piles spaced at intervals along a clay cutting or embankment slope can provide an effective remedial measure to reduce the instability of a slope that has either failed or is showing signs of failure. The technique can also be used to steepen slopes. The report includes a literature review and draws on both physical and numerical modelling work, as well as extensive case study information, in order to identify design implications and develop design procedures. It is the first in the new Insight series of reports, which provide a multifaceted overview of the key issues in a given subject area, thus forming an effective introduction to a topic.

During 2009, we established a Ground Engineering Centre of Excellence at our offices in Edinburgh. TRL has a long history in ground engineering research and this move reinforces the importance of high-profile work undertaken in Scotland in recent years, including that for Transport Scotland on landslides, which is recognised and respected both nationally and internationally.

The centre will provide a focus for our activities in ground engineering, and will embrace both traditional and newer environmental and sustainability activities, including: investigation and materials; earthworks; instability; failure and risk; structures and structural assessment; geosynthetics; instrumentation and monitoring; geotechnics of pavements; resource management; and sustainable techniques.

We are currently involved in some particularly innovative work looking at the reuse and recycling of geomaterials; ground source heat/energy; and carbon footprinting, audits and life cycle assessments of earth structures.

Our research on landslides has continued, with further work for Transport Scotland assisting with the implementation of recommendations made since landslides severely affected the trunk road network in August 2004. Work also continues on the development of forecast models based on rainfall intensity and duration. We are also part of a 25-partner consortium that is undertaking a major EU project, "SafeLand", to help develop landslide risk assessment and management approaches at a European level as well as addressing global climate change. In parallel, the potential for collaborating on landslides with the University of Seoul in the Republic of Korea is being investigated. This has included a five-day exploratory visit to undertake field work, lecturing and discussing issues of importance to risk management in the Republic of Korea. The visit attracted considerable media interest and included appearances on Korean national television.

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Asset management systems in Africa

Most countries in the world have limited resources and funds to adequately manage their road network. This is particularly so in Third World nations, such as those in Africa. In these countries, it is vital that scarce resources are utilised in an effective and appropriate manner. We have been working in collaboration with several road authorities in Africa to develop a sustainable Pavement Management System (PMS) to enable them to prioritise road maintenance activities on their road networks, within their financial constraints and based on sound economic criteria.

Over the past few years, we have developed the Road Data Manager (RDM) system. This is a centralised database for storing and processing information on a country’s road network. The information stored in RDM includes location (referencing system), inventory, surface condition, roughness, traffic levels, pavement layer thickness and works history. The system has been implemented in Malawi, the Gambia and on the island of Mauritius. RDM divides the road network in each country into links that are homogeneous in terms of traffic levels, carriageway width and surface type. The location (using the Global Positioning System, GPS) is recorded at the start and end of each link and at each bridge. The inventory items stored in RDM vary from country to country, but usually include road characteristics and furniture, social information such as police stations, hospitals, schools and trading centres, and the land use around the road.

The data can be processed and used to produce customised reports, which may be in tabular or graphical form and which provide useful information on the state of the road network for managers, planners and maintenance departments.

In addition, the RDM processes the data to produce a road network export file that can be imported directly into the Highway Management and Development tool, HDM-4. HDM-4 provides a powerful system for the analysis of road management and investment alternatives, producing economically justified, prioritised works programmes for user-specified budget scenarios.

In Malawi and Mauritius, we have enhanced their management systems by incorporating a Bridge Management System (BMS) within RDM. The BMS comprises an inventory module and a condition module.

We have trained local teams in bridge-inspection techniques, and the data collected during surveys are input into the bridge condition module. The inspection teams look for a range of possible defects on each of the bridge components, and the defects are assigned a score based on their extent and severity. The individual defect scores are used to calculate a condition score for each component, and the condition scores for each component are combined to calculate the overall condition of the bridge. The BMS uses the condition of the bridge and its components to prioritise the bridge stock according to its maintenance needs.
South East Asia Community Access Programme (SEACAP)
The South East Asia Community Access Programme (SEACAP) was initiated by the Department For International Development (DFID) in 2004, and was completed in June 2009. The programme aimed to improve the sustainable access of poor people in rural communities to health, education, employment and trade opportunities. Over 30 projects were carried out in Vietnam, Cambodia and Laos PDR on low-cost and sustainable road construction. Our involvement has included:

- Pavement and surfacing trials, using locally available materials in Vietnam
- Pavement, surfacing and geometric standards, specifications, design guide and site trials for low-volume rural roads in Lao PDR, taking materials, climate, terrain, traffic and construction capability into account
- Guidance on the use of suitability of earth roads in Cambodia
- Standards and specifications for low-volume rural roads in Cambodia
- Updating of a manual for low-cost water crossing structures in Cambodia

SEACAP’s approach allowed planners and constructors to experiment and test new techniques, tailoring each project to the local environment and materials available. This same approach is now being taken forward in Africa under a new DFID-funded programme – the Africa Community Access Programme (AFCAP) (see below).

Africa Community Access Programme (AFCAP)
We have been instrumental in developing initiatives designed to increase the local capacity for implementing low-volume road technologies and to address the challenges of providing reliable access for poor communities in sub-Saharan Africa for AFCAP. The programme of work for AFCAP began in 2008 and is due to be completed by 2013. It is a DFID-funded programme of research, knowledge dissemination and training designed to address the challenges of providing safe and sustainable access to poor communities in this part of Africa.

We have provided technical support for pilot projects on low-volume rural roads in Mozambique for the Mozambican National Roads Administration (ANE), and have been commissioned to provide technical designs, contractor training and monitoring for a second phase of the project.

We have also developed pavement design standards and specifications for low-volume roads in Ethiopia.
In order to improve safety, we need to deal with all the components of the transport system. This involves studies that focus on persuading and enabling motorists to drive in as safe a manner as possible and to be aware of risks, as well as making sure that both vehicles and infrastructure aid the driving task and provide reasonable protection against injury when accidents occur. Our work on road and vehicle safety therefore covers a broad spectrum of research and consultancy.

TRL’s vehicle safety engineering research covers crashworthiness, occupant and pedestrian protection, advanced safety systems, commercial vehicle safety, motorcycle safety and road restraint systems. Our safety research uses accident data to identify trends in the frequency, severity and causes of accidents and injuries. This information is used to advise on the setting of casualty reduction targets and to help develop measures to improve safety and to monitor effectiveness once in service. We also work to find ways of influencing the attitudes and behaviour of road users by training, testing, education, enforcement and the use of in-vehicle technology. Our international road safety researchers work with overseas clients to develop road safety policies and strategies and assist with institutional strengthening.

Our customers are mainly government-based organisations. However, the number of customers from the commercial sector has continued to grow and forms a substantial proportion of our work. Our commercial customers include insurance companies, vehicle and equipment manufacturers, operators of vehicle fleets, rail companies, car-racing teams and many others.

Our research is supported by several large-scale facilities. These include both car and HGV driving simulators, a test track, a full-scale vehicle crash test laboratory, a drop tower, “sled” test rigs and other specialist test rigs.

The following section of the Review highlights just a selection of this research undertaken during 2009.

DRIVING SIMULATION

2009 has been the final year of the European Union (EU)-funded project TRAIN ALL. This has been an ambitious project involving 16 partners across Europe looking at developing new driver training tools and materials for all categories of licence acquisition training. Although new aids to teaching are becoming available in the forms of distance learning programmes, interactive PC-based lessons and tests, and fully interactive driving and riding simulators, Europe has lacked an integrated approach or harmonised platforms for development. The TRAIN ALL project has sought to review current training and licensing practices across Europe and to determine the current levels of use of simulation and distance learning tools. Recommendations have then been made for the classification of different types of system, and links made to the appropriate curriculum content. The aim has been to develop a range of driving and motorcycle riding simulators that can share road environments and particular advanced modules (such as for emergency service drivers) on an open-platform environment. TRL has been particularly active in research into the potential classification and accreditation schemes for such simulators and in working with industry to establish cost-effectiveness evaluations.

There seems to be very great potential for the use of simulators in training for all types of vehicles, from motorcycles through to HGVs and public service vehicles[71]. They are able to play a role in training drivers in the skills needed for licence acquisition, and also in continuing skills development as part of continuing professional development courses for commercial drivers. For example, last year’s success in truck driver training also continued in 2009. The programme, which provides fuel efficiency training, continues to provide clients with cost-effective driver education and real-world fuel savings.

The simulator facilities have been host to several interesting developments resulting from cross-divisional reinvestment projects and from preliminary proof-of-concept work for commercial customers.
In an exciting new study, we have developed our ability to manipulate the physiological state of drivers and then record their behaviour and performance. The photograph below shows stress being induced in the truck driver by varying the CO₂ concentration in the air (with the help of a method established at Bristol University), with the responses measured including heart rate variability, respiration rate and blood pressure. It was shown that anxiety could be safely increased for relatively long drives, and we were able to quantify the levels of stress and discomfort that could be correlated with changes in driving performance.

A behavioural approach to research on driver stress and the perception of risk has been taken by Britta Lang as part of her PhD research, supervised by Professor Ray Fuller at Trinity College Dublin. She has used TRL’s car driving simulator to show animations of various traffic environments at different speeds to drivers, and taken subjective measures of stress and workload to test theoretical models of the influence of task demand on perceptions of risk.

The work not only provides insight into the relationship between speed and perceived risk, but also shows interesting differences between drivers of different ages and experience levels. This work will be extended in the final part of the research to investigate other factors of hazard perception and situation awareness.

Driver perceptions are also being tested in TRL’s car driving simulator in relation to the ability of drivers to discriminate and interpret vehicle performance characteristics. We are interested to know how features such as response lag, noise, vibration and acceleration affect the drivers’ views of the comfort, quality, desirability and value of the vehicle.

While TRL is renowned for using either the test track or one of the simulator facilities for research into driver behaviour, two large European collaborative projects have commenced in 2009 that will add a complementary stream to these studies in the form of what is becoming known as “naturalistic” studies. These seek to employ advances in sensor and recording technology in order to use real vehicles in natural driving settings. INTERACTION will focus on car drivers and 2 BE SAFE will be the first EU project to focus on motorcyclists. Cars and motorcycles will be equipped with sensors and video recording equipment that can record data at very similar levels to that captured in the simulators, and will be used to provide evidence of current driver/rider behaviour. This work is being supported by the Department for Transport (DfT), Harrogate City Council and Suzuki, and will provide information that has not been previously available from real road settings.

Finally during 2009, there was a range of excellent magazine, radio and TV publicity for TRL’s work with the driving simulator, including driver distraction, driver fatigue and eye-steering coordination of racing drivers. Journalists from the Daily Mirror and the Daily Telegraph came to experience the effects of various distractions when driving in the car simulator.
Research highlights: Road and vehicle safety

ACCIDENT RECONSTRUCTION

We have conducted a series of simulations with the Vehicle Engineering Group and its client BP to develop a "rollover protection device" for use by its fleet in areas such as Algeria and other parts of North Africa. Currently, BP is using a Fédération Internationale de l'Automobile (FIA – Formula 1) standard rollover protection device which, although effective, is costly to install and based on a functional specification not related to the transport of petrochemicals. BP looked to TRL for advice on a standard that the company could adopt that provided the necessary protection to occupants but at a realistic commercial cost. This work was validated using HVE modelling1 and its 3D collision algorithm, DyMESH, in simulating vehicle rollovers. The first stage involved replicating vehicle damage from “drop tests”, where the vehicle is simply dropped on its roof.

The tests looked specifically at the loading conditions and accident damage to the vehicle, and compared this with the same parameters from the earlier accident investigations. This work has now fed into the next phase, which will involve full-scale testing and development of the rollover protection device.

Other work on car rollover mechanisms can be found in the full paper included in this Review beginning on p. 71 and in the list of publications[68].

VEHICLES AND BIOMECHANICS

The Vehicles Group has started to develop a dummy to test fall arrest systems that are used to protect people who work at height. Fall arrest systems are currently tested to various standards using drop weights. Nonetheless, it is known that systems that pass these tests can fail catastrophically in the field as the simple weight will not have performed in a similar way to a human body under similar circumstances. Informal tests are also currently conducted using various crash test dummies, and these are better at highlighting performance problems with the fall arrest systems. However, there is no standard definition of the dummy that should be used, and those that are used in the industry are old and cannot be repaired because spare parts are no longer made. The work is thus focused on adapting the Hybrid III crash test dummy for fall arrest use, including modifications to the pelvis, abdomen, neck and clothing to ensure appropriate interaction between the dummy and the harness.

On a related theme, TRL has benefitted from its extensive academic links to be able to promote applied research. A European Commission (EC)-funded Marie Curie Research Training Network PhD student from Imperial College London was seconded to TRL for two months during 2009 to study the effects of head impacts during motorcycle accidents. The study involved the use of a TRL crash test dummy and TRL facilities to carry out a series of drop tests. The dummy was fitted with a motorcycle helmet and dropped onto specially designed anvils that are used in motorcycle helmet testing and certification (see p. 46 of this Review for further details of the safety helmet drop test rig). The test results are being used to validate a finite element (FE) computer model, which is looking at the effect on the rest of the body of head impacts.

ACCIDENT RECONSTRUCTION

Modelling rollover dynamics

The second stage involved reconstructing a series of real-life accidents recorded by BP’s accident investigators in Algeria. The purpose of this was to predict the forces that may be induced in the vehicle during the rollover event, and also the accident damage. The third and final part involved using simulation to create a series of mock laboratory tests following the typical Federal Motor Vehicle Safety Standard FMVSS208 in order to determine the most representative laboratory conditions under which full-scale rollover tests should be performed.

Preparing a test dummy

On a related theme, TRL has benefitted from its extensive academic links to be able to promote applied research. A European Commission (EC)-funded Marie Curie Research Training Network PhD student from Imperial College London was seconded to TRL for two months during 2009 to study the effects of head impacts during motorcycle accidents. The study involved the use of a TRL crash test dummy and TRL facilities to carry out a series of drop tests. The dummy was fitted with a motorcycle helmet and dropped onto specially designed anvils that are used in motorcycle helmet testing and certification (see p. 46 of this Review for further details of the safety helmet drop test rig). The test results are being used to validate a finite element (FE) computer model, which is looking at the effect on the rest of the body of head impacts.

It is increasingly important for safety design decisions to be based on empirical evidence, and the testing and gathering of realistic data must inform future product development. A good example of the way in which TRL is helping in practical safety design is given by our work with Devon County Council. Four full-scale impact tests with Nissan Micras were conducted at the Impact Test Facility (ITF) to investigate the severity of hitting the kind of solid oak signposts which are currently sited within the Dartmoor National Park.

The first two tests (one at 35 kph, and the second at 70 kph) were conducted on the design of post currently installed. Two subsequent tests (with the same impact parameters) were then carried out on a modified post, and the difference in impact severity calculated. The result of this testing is to be used to maintain/modify the hundreds of posts currently installed.

Our European work continues to influence international road safety and serve as the basis for active links with regional academia. COVER is an EC 7th Framework project started in April 2009. This three-year project will undertake a range of coordination and dissemination activities related to a cluster of four Framework Programme 7 (FP7) “biomechanics” projects. TRL is involved in two of these: THORAX and EPOCh. COVER will also undertake an accident analysis to provide guidance to THORAX and THOMO (another biomechanics cluster project) regarding thorax injury mechanisms in frontal impacts and how best to target new dummy designs and injury criteria to reduce the overall burden of thorax injuries in frontal impacts.

The concept of EPOCh (Enabling Protection for Older Children) is to improve safety for older children travelling in vehicles. This is being done by extending the development of the protocols, test procedures and measurement tools necessary (in view of the recent changes in legislation) to carry out impact tests for restraint systems designed to protect older and larger children in vehicle collisions. The results of this will directly impact European (and potentially worldwide) testing. TRL’s involvement has been to provide Cooperative Crash Injury Study (CCIS)’ data analysis. This has involved analysis of frontal and side impacts, focusing on the injury patterns for older children (aged 6–12) in these accidents, the mechanisms of injuries and the effects of using different types of child restraints.

Members of the vulnerable road users and vehicle crashworthiness groups were awarded a project by Allied Vehicles Limited to compare the wheelchair accessibility of the Peugeot E7 with two similar vehicles by other manufacturers: an LTI TX4 and a Mercedes Vito. A physical assessment of each vehicle was carried out at TRL, which included an investigation of the interior manoeuvring space using dummies seated in wheelchairs. All three vehicles were wheelchair accessible and capable of carrying a high proportion of wheelchair users. However, there were some differences between the vehicles, which were highlighted in the project.

During August 2009, TRL launched its new independent five-star rating scheme for child restraint systems. TRL’s input to the science behind the scheme has been funded mostly by DfT. TRL has invested time to fine-tune the assessment and rating protocols so that the scheme discriminates between different levels of product. Over the past 18 months, we have spent time discussing and developing the scheme with leading retailers and manufacturers and with the Automobile Association (AA).

The new rating scheme will provide rigorous and independent performance ratings for all seats tested, and will enable consumers to make comparisons and informed decisions about which product best meets their requirements. Stars will 2 CCIS is one of the world’s largest studies of car occupant injury causation. Each year, the project investigates more than 1000 crashes involving cars. The project is managed by TRL.
be awarded – from one star through to a maximum of five – and ratings will be publicly available on TRL’s web site, which will hold all the latest information. Further information of this scheme can be found on p. 49 of this Review.

Another strand of activity has been to continue research into vehicle design. There has been much interest and debate in recent years about the costs and benefits of the introduction of larger vehicles on to our road system. The Integrated Safety Team have been drawing together the results of extensive consultation with the trailer and axle manufacturing industries, and vehicle dynamics simulation undertaken by Cambridge University, to understand the economic implications of permitting longer semi-trailers – either without steered axles, with existing steered axles or with advanced “active” axles that enable perfect path following.

**CRASH INVESTIGATION**

The crash investigation team have continued to work on large strategic research programmes including the On The Spot (OTS) and CCIS initiatives. These projects, which gather real-world crash and injury data, are invaluable sources of information on vehicle performance and the subsequent injury patterns for road users. The results not only inform policy makers about the relative importance of different accident configurations, but also point towards appropriate testing procedures for future systems. For example, we have continued to work on a side-impact study project to determine the cost benefit of new side-impact tests using CCIS data and to consider the effects of drivers’ speed on frequency and typology of road accidents.
During 2009, the first part of a Pedestrian and Cyclist Injury Study began – the scoping study – which defined in detail the methodology and protocols that TRL proposes to follow when conducting a large-scale study. The intention is to begin the study in London and to involve a team of accident investigators who will attend the scene of collisions involving pedestrians. From this data, the effectiveness of new EU regulations for car-front pedestrian-friendly design will be investigated.

**BEHAVIOUR AND ATTITUDES**

Work-related road safety has continued to develop as an important safety theme, and commercial companies are increasingly keen to adopt best practice – both to support their duty of care responsibilities and to maximise their commercial advantages through reductions in insurance premiums, lost output, damaged plant and so on. TRL has continued to liaise directly with companies to provide best practice advice and support tools in the form of interactive CDs, literature and personnel briefings[47]. Based on data from a large sample of people driving for work, TRL has, in conjunction with insurer AIG, developed a web-based psychometric test for employees who drive for work. This online assessment is designed to identify at-risk drivers who may be in danger of having a crash while driving for work, in order that preventative action can be taken.

The tool requires drivers to complete a set of questions designed to pinpoint key areas of risk. It takes approximately 40 minutes to complete the questions. The item pool has been collated on the basis of an extensive review of the scientific literature and of thorough piloting with a large number of at-work drivers to ensure that it is appropriate and easy to understand.

The Driving Profiler considers drivers’ work-related driving and their driving-related behaviours, as well as their driving-related “attribution framework” and knowledge of the Highway Code. Individuals who try to give socially desirable answers to create a favourable impression can be identified by the tool.

While traditional profiling tools are typically not specific to the culture of the organisation or the conditions in which it operates, the TRL Driving Profiler assesses the safety culture and takes account of the organisation’s operations in order to highlight conditions that may put the driver at risk.

To create the output, drivers’ responses are compared against norms for similar driving populations, and risk ratings are calculated for the separate areas to create risk profiles. These are fed back to individual drivers with detailed explanations. Managers receive a summary report on their part of the business, which highlights the drivers who may be at risk and provides recommendations for remedial action plans (e.g. further education, training, e-learning, in-vehicle assessment or revision of overly demanding work schedules). The tool allows comparison between business units in terms of summarised risk ratings and safety culture indicators.

Continuing validation of the tool, using retrospective and prospective correlation methods with relevant criteria such as work-related road crashes, traffic offences and driving performance, ensures that drivers are correctly classified into appropriate risk categories.
Driver training continues to be a prime focus for our research. The Cohort II Study of learner and novice drivers was a major six-year study, funded by DfT, which set out to provide an up-to-date picture of how learner drivers in Great Britain undertake driver training and testing, and of their subsequent experiences as new drivers.

The findings from the Cohort II Study were reported last year. Two more recent reports describe additional analyses carried out on this invaluable data source. Published Project Report PPR427[52] describes further analyses of the accidents, attitudes and self-reported behaviours of drivers who passed their practical test on the first occasion that they took it. It also examines their performances on the theory test and the practical driving test, and compares them with drivers who took more than one practical driving test.

A second study (reported in PPR426[53]) describes further analyses of the accident data that was collected in the Cohort II Study. It employed different procedures to those used in the main study, and approached the data from a different point of view. It did so by posing two questions. The first of these asked when new drivers have their first accidents, and what the factors are that influence this. The second asked what effect accidents have on the attitudes and self-reported behaviours of the drivers who are involved in them.

Our work on this topic has also looked at the whole question of skills and experience[3]. New drivers, especially young new drivers, are at greater risk of having a road collision when they start their driving careers. In this work, we consider the factors that are associated with the collision risk of new drivers. Specifically, we review the literature for evidence relating to the effectiveness of three factors in lowering this risk: experience; driver education and training; and minimising new drivers’ exposure to high-risk situations.

3 This work will be published as Insight Report INS005 in February 2010. The full reference is Helman S, Grayson G B and Parkes A M (2010). How can we produce safer new drivers? A review of the effects of experience, training, and limiting exposure on the collision risk of new drivers. TRL Insight Report INS005. Crowthorne: Transport Research Laboratory.
Our research suggests that all jurisdictions trying to lower the collision risk of new drivers should consider adopting some form of graduated driver licensing system. The precise make-up of such a system will probably vary according to the needs and practices in any particular jurisdiction. However, it seems likely that systems that set a minimum amount of time spent learning, that limit exposure to high-risk situations early in post-licence driving and that stimulate much greater amounts of on-road experience will have the greatest effects overall. The benefits in terms of lowering collision risk are likely to be largest for the youngest new drivers.

Within Europe, TRL has recently begun work on three collaborative research projects funded by ERA-NET ROAD, which is a European Commission (EC) initiative dedicated to formulating new transnational research and to coordinating cooperation on existing research programmes. TRL is collaborating with a number of European research institutes and universities to deliver RISMET, ERASER and SPACE. Road Infrastructure Safety Management Evaluation Tools (RISMET) will develop new accident prediction tools to be used by authorities, Speed Adaption Control by Self Explaining Roads (SPACE) will identify aspects of road design that can be used on rural roads to reduce vehicle speeds, and Evaluations to Realise a common Approach to Self-explaining European Roads (ERASER) will develop a framework to make road categories (and therefore also expected behaviour) clear to road users in a consistent manner across Europe.

*Road-narrowing measure employed on a rural road to affect reductions in speed*
Climate change has been recognised as the greatest environmental challenge facing the world today. The effect of past greenhouse gas emissions on climate and weather pattern is already noticeable, and the associated environmental, economic and social impacts are felt at the global and local scale.

The latest report of the International Panel on Climate Change (IPCC) provides the evidence base. This demonstrates the necessity of reducing emissions of greenhouse gases and of adapting to the inevitable climate change resulting from past emissions. The UK Government is leading the way through the passing in December 2008 of the Climate Change Act, which gives legally binding targets to achieve a reduction in greenhouse gases of at least 80% over 1990 levels by 2050, and transport has a key role to play in achieving this reduction. The transport sector accounts for a fifth of global CO₂ emissions, and transport energy-related CO₂ emissions are predicted to increase by 1.7% a year from 2004 to 2030. To meet long-term reduction targets, the transport sector must contribute more to emission reductions. This will require a fundamental change in the day-to-day processes and practices of individuals and organisations.

Our research this year has continued to focus on understanding the short-term and long-term implications of climate change, and on identifying the changes required to achieve the reduction targets. This will enable us to provide guidance on the development of policies and strategies that encourage more sustainable energy and resource use; to undertake research on the effectiveness of particular mitigation and adaption measures; and to provide education and training on climate change. We are also working with a network of international organisations to identify the overall policy framework, instruments, indicators and financing mechanisms that will support a sustainable transport system. Finally, we have continued our research on specific topics related to sustainable communities, emissions and air quality, noise, and resource and waste management.

We contributed to the Bellagio Declaration on Transportation and Climate Change, which resulted from a meeting held in Bellagio, Italy, in May in order to build a consensus on the required policy response to the growing CO₂ emissions from transport in the developing world. The declaration was made by representatives from 18 organisations working on transport and climate change. The work at Bellagio has grown to form...
We have been very active in this area over the last year – as demonstrated, for example, by:

- Our work to support the National Development Planning Agency (BAPPENAS) of the Republic of Indonesia in developing a “road map” for transport and climate change. The project consisted of working on the ground with local policy makers and transport specialists to develop strategies to mitigate future carbon emissions and adapt infrastructure to a changing climate.

- Authoring sourcebooks on behalf of the German Organisation for Technical Cooperation for policy makers in developing cities, which provide easily accessible information on sustainable transport and address the key issues in the creation of successful strategies.

- Undertaking research to understand the policy options, and to identify future methodological needs, in order to measure carbon reduction resulting from transport schemes in developing countries. This will allow developing countries to obtain funding by selling carbon credits for these schemes to industrial countries using the Clean Development Mechanism (CDM). The findings from the project have been disseminated through side events at COP meetings.


Supporting a “green” economy
We are working with the United Nations Environment Programme (UNEP) to develop the Green Economy Report, which will provide policy makers with information allowing them to integrate the climate agenda into policy decisions for a green economy. The Green Economy Initiative (GEI) is designed to assist governments in “greening” their economies by reshaping and refocusing policies, investments and spending towards a range of sectors – such as clean technologies, renewable energies, water services, green transportation, waste management, green buildings, and sustainable agriculture and forests.

Policy instruments for a sustainable future in China
During 2009, we undertook a project which examined policy integration issues and a Strategic Environmental Assessment (SEA) for the energy and transport sectors of the People’s Republic of China (see also the section on SEAs, below). The project was financed by the European Commission’s (EC) Programme Asia Pro Eco II and co-financed by participating project partners. We are helping to build transportation and energy-use systems in China aimed at achieving sustainable development. The main focus of the project was the integration of environment in transport and energy planning, at the policy and the administrative level. As part of this process, we undertook two case studies on transport and energy planning. The key outputs were recommendations for SEAs and Environmental Performance Indices (EPIs) based on research and guidance material produced by the lead partners. We also provided support in drafting legislation (through guidance and recommendations) and capacity development. The outputs from the project can be found at www.sea-in-china.com/

Developing practical ideas for low-carbon transport in developing countries
We have a long history of enabling policy improvement in the developing world. With CO₂ outputs from developing nations becoming increasingly prevalent, the challenge is to allow for low-carbon development which is also beneficial economically and socially.
Navigating European efforts
We have been working with the European Environment Agency (EEA) to produce the annual Transport Environmental Reporting Mechanism (TERM) reports. There have been several publications, including:

- Transport at a crossroads (2008)
- Climate for a transport change (2007)
- Success stories within the road transport sector on reducing greenhouse gas emissions and producing ancillary benefits (2008)
- Beyond transport policy – exploring and managing the external drivers of transport demand (2008)

In addition, we have produced a number of indicator factsheets.

Supporting adaptation to climate change
We have developed innovative climate change indicators to monitor regional resilience to climate change impacts, as well as developing climate change strategies for local government. We have also developed a regional framework for improving adaptation actions. We produced the UK Department for Transport’s (DfT) guidance document for local highway engineers on the impact of climate change on the highway network and actions that can be taken to reduce this. We have also been involved in the European Climate Change Adaptation Project (ESPACE), and have been appointed to the EC’s Environment Management Group – Urban Thematic Strategy. Members of our project team have been seconded to the UK Government’s adaptation team, and we hosted the UK Climate Impact Programme’s UKCIP08 User Forum (now launched as UKCP09).

SUSTAINABLE COMMUNITIES
Sustainable mobility in cities
Currently, around 95% of all mobility is powered by fossil fuels. This is not viable in the long term; in part because of the restrictions that will be increasingly placed on the use of fossil fuels (as part of the response to climate change), but in addition, because the world is running out of relatively cheap sources of oil. More generally, many of the major cities of the world suffer from acute congestion that is detrimental to their ability to function effectively. Solutions are urgently required in order to help reduce our reliance on fossil fuels for transport, and in response to this need we are carrying our research for Shell to develop “route map(s)” for managing the transition to more sustainable mobility.

The project is addressing the following issues: what needs to be done; who needs to do it; the order in which the various tasks need to be done, and over what timeframe; and what the costs should be, and who should pay for them. In addressing these issues, a wide range of political, economic, social and technological questions are being considered.

Smarter Choices
We continue to undertake research that focuses both on practical measures and on the social and psychological factors influencing travel choices and travel behaviour change. We have recently reviewed the evidence about travel behaviour and the drivers and barriers for behavioural change for the Rail Safety and Standards Board (RSSB); and, in a second study, we reviewed evidence about how different forms of transport could be better integrated, in order to encourage more sustainable travel behaviour.

We have been involved in a major study for DfT to evaluate the performance of the UK’s three “sustainable travel towns”. DfT provided five years of funding to Peterborough, Worcester and Darlington in order to test the potential for promoting walking, cycling and bus use employing a range of “smarter choice” measures. This project is investigating the effects of that funding on people’s travel choices, and the implications for encouraging a more widespread behavioural shift through encouraging such measures across the country.
We are contributing to a similar piece of work for Transport for London (TfL) in order to evaluate travel behaviour changes resulting from “smarter travel” work. TfL has provided funding for the London Boroughs of Sutton and, more recently, Richmond to encourage more sustainable travel habits using a range of “smarter choice” measures. Our work is focusing on assessing changes in attitudes and behaviour by residents relating to transport options as a result of the activities in those areas, based on both primary survey work and existing data sources.

In a different piece of work for TfL, we are focusing on the links between travel plans and health. This includes assessing the effectiveness of existing travel plans in London on achieving modal shift, and promoting more active travel (particularly walking and cycling). It also involves assessing available data on how travel choices affect sick leave and overall physical activity.

Meanwhile, we continue to be involved in a large-scale ongoing programme of work assessing the quality of pedestrian environments. This includes use of a specific auditing tool (PERS), which enables the identification and prioritisation of key factors in an area that could be altered in order to make it a more pleasant environment in which to walk – and to encourage people to walk more, generally[101].

Other work on this and related topics, published during 2009, can be found by consulting the list of publications located at the end of this Review[100, 101, 102, 108].

**STRATEGIC ENVIRONMENTAL APPRAISAL (SEA)**

In order to support the development of the next round of English Local Transport Plans (LTP3), we have remained at the forefront of guidance development by updating DfT’s guidelines on the SEA of Transport Plans and Programmes (TAG 2.11). This project required liaison with other organisations – including Natural England, the Environment Agency and English Heritage – in order to ensure that the guidance was appropriate for taking forward their particular interests in the SEA process.

We have continued to provide SEA capacity building to public bodies, by undertaking training workshops. This year’s workshops have included training for Natural England officers to help them fulfil their organisation’s role as a statutory consultee in the SEA process. The aim of the workshops was to provide the delegates with a good grounding in SEA and provide recommendations as to how they could maximise the benefits to Natural England when providing consultation responses.
EMISSIONS AND AIR QUALITY

During 2009, our Air Pollution and Emissions Group continued to expand, and now has a complement of 15 staff. It offers a comprehensive suite of research and consultancy services across the emissions, fuel consumption and air pollution monitoring disciplines, combined with a growing involvement in projects covering impact assessment. It should be noted that the range of monitoring services offered by the group is described in the section of this Review beginning on p. 49.

Following the 2008 DfT consultation on the revision to the UK’s road transport emission factors, we released the final set of factors and associated reports in early 2009 [81, 85, 86]. These represent the first major revision to these national emission factors for eight years. The launch was supported by a series of presentations at seminars and workshops. The associated reports examined the various approaches to hot-start emission modelling and cold-start and evaporative emissions, as well as fuel quality effects.

The investigation of new transport activity data and bottom-up emission modelling approaches was continued with dissemination events on the use and application of a prototype Geographic Specific Emissions Inventory (GSEI). This European Environment Agency (EEA)-funded initiative, seeks to identify new data streams that could be used to improve the temporal and spatial disaggregation of emission inventories, focusing initially on road and rail transport.

The expansion of Managed Motorways across the Highways Agency (HA) network has been designed to make use of a range of traffic management measures to control speeds, add capacity and inform road users of conditions on the network. As part of the development and roll-out of these operational regimes, we have been involved in the development of emissions assessment tools and the evaluation of their impacts.
on exhaust emissions, fuel consumption and local air quality – focusing on the motorway network around Birmingham. Supporting work is also being undertaken on the M20 Managed Motorway, where we are investigating the ability of the operational regime to assist in improving roadside air quality. A revision to the Managed Motorway emission calculator is also being undertaken, through a combination of instrumented vehicle measurements and instantaneous emission modelling.

During 2009, we commenced research to provide DfT with a new and enhanced rail energy and emissions model. The model builds upon the earlier rail modelling developments within the European Union (EU) Assessment and Reliability of Transport Emission Models and Inventory Systems (ARTEMIS) project, and is being undertaken in collaboration with Atkins Rail[90, 105].

Environmental Impact Assessments (EIAs) are undertaken as part of the development of new road schemes. EIAs include a consideration of local air quality (focusing on particulate matter and nitrogen dioxide) and changes in the regional emissions of CO₂. We have, in collaboration with Halcrow Barry, been undertaking research for the National Roads Authority (NRA) of Ireland in order to evaluate the effectiveness and application of Air Quality Impact Assessments (AQIAs) for new national road schemes. This has involved an evaluation of the performance of the original scheme emissions and AQIAs against conditions once the scheme is in operation. The results will be used to make recommendations on the potential future enhancement of the NRA AQIA guidelines, including the identification of potential emission and air pollution mitigation options.

In support of the air quality review and assessment process, we have also been involved in a range of modelling investigations for the provision of updated screening assessments, and detailed and further assessments for a range of UK local authorities. Our role as Secretariat of the Dutch Air Quality Innovation Programme (IPL) has continued during 2009, and will result in the development of guidance on the benefits of a range of transport emission mitigation strategies, aimed at targeting compliance with European air quality limit values.

Our work for TfL has continued, with support in the areas of low-carbon taxis, hybrid buses and scheme assessment. In collaboration with Air Quality Consultants, we are currently reviewing and developing pilot studies for the improvement in particulate matter concentrations at a series of pollution hotspots across London.

Air pollution monitoring has expanded to include site selection, equipment provision and installation, data collection, ratification and reporting. Throughout the year, continuous monitoring has been undertaken at over 25 locations, largely focussing on compliance with Air Quality Strategy (AQS) objectives and EU limit values for nitrogen dioxide and particulate matter. The most comprehensive monitoring and analysis continues through the operation of HA’s long-term network of roadside air pollution monitoring stations. These sites are equipped with a large range of regulated and unregulated pollutant measurements, and are combined with local meteorological and traffic measurements. This network allows for an in-depth analysis and an improvement in the knowledge of the trends in emissions and its relationship with roadside air quality. Further information on the monitoring services operated by the Air Pollution and Emissions Group is contained in the section in this Review on specialist consultancy services (see p. 43).
Research highlights: Environment and sustainability

Assessment of options for Noise Action Plans
TRL was commissioned by the Scottish Government to undertake a review of the different low-noise road surfaces currently available, and to comment on their relevance and suitability for use in Scotland as a mitigation measure within the END’s Noise Action Plans. This review, which included consultation with relevant stakeholders, took into account not only acoustic performance but also safety and skid resistance, structural durability, environmental sustainability and whole-life costing.

Reducing the noise impacts of night-time freight movement
HGV movements in urban areas are often constrained during night-time and/or weekend periods by local regulations, which have been put in place to minimise noise impacts. If such night-time delivery restrictions could either be relaxed or removed, where appropriate, there are significant potential benefits, primarily associated with reduced daytime congestion. We have undertaken a study for DfT to review the needs for, and the feasibility of, a permissive low-noise certification scheme for HGVs and their operation. This has included preliminary development of the test methodologies necessary to identify suitably “quiet HGVs”.

Improved understanding of the durability of noise mitigation measures
We have continued with research for HA to improve understanding of the acoustic durability of noise barriers and low-noise road surfaces. The performance of these measures when new is well known as a result of product certification. However, information on their long-term noise reduction performance is not well documented. The focus has been on the undertaking of comprehensive measurement programmes on timber noise barriers of different ages (using state-of-the-art in situ assessment methods) and on recently laid/existing road surfaces, using roadside measurement techniques as well as measurements taken in close proximity to vehicle tyres. The results for barriers will provide indicative information on long-term acoustic durability and assist HA with the incorporation of recently introduced EN standards on performance and CE marking into their barrier specifications. The results for surfaces will provide information on long-term acoustic durability and further evidence to HA on the suitability of such measures for use as mitigation tools in Noise Action Plans. The results will also be used to update and improve noise prediction modelling and mapping methods.

Recent noise mapping, and the preparation of draft noise action plans to reduce environmental noise in accordance with the European Directive on the Assessment and Management of Environmental Noise (2002/49/EC; END), have increased public awareness of the issue of noise nuisance from transport systems. We have undertaken, and are continuing with, a wide range of noise mapping projects, the outcomes from which play an important role in helping to ensure the development and implementation of appropriate, effective and robust noise action plans by the relevant stakeholders.

Improved understanding of the durability of noise mitigation measures

Microphone array and speaker system used to test the acoustic performance of noise barriers

Roadside measurements of tyre/road surface noise

Microphone array and speaker system used to test the acoustic performance of noise barriers
The disposal of post-consumer tyres is an issue of considerable importance both within Europe and further afield, with some 46 million tyres (460,000 tonnes of material) being scrapped in the UK alone each year. With the passing of the EC Landfill Directive, which outlawed the disposal of both whole (2003) and shredded (2006) tyres to landfill, alternative uses for tyres are being examined.

Tyre-derived rubber materials cover a wide range, from shred to crumb, and are used in an equally wide variety of applications, from drainage in landfills to sports and play surfaces. One particular application is the construction of bales from disused tyres for use in construction. We have been involved with tyre bales and their potential use in construction for over a decade, undertaking research in the UK and the USA to define material properties and behaviours, and producing guidance on design, specification and construction. Recently, we have been involved in the design, construction and monitoring of a tyre bale embankment on the A421 improvement, the M1 Junction 13 at Bedford, close to Brogborough Lake (the A421 trunk road connects the A1(M) and the M1). The embankment in question passes over an infilled lake and the ground is very soft, thus requiring that the embankment fill materials be lightweight in order to limit settlement both during and after construction. We are acting as an adviser to designers, constructors, clients, government bodies and the UK Tyre Baling Association, as well as tyre bale users/manufacturers in France and Croatia.

WRAP and EA have produced a quality protocol for tyre-derived rubber materials in order to accompany the existing Publicly Available Specification PAS107:2007, Specification for the manufacture of size reduced tyre materials. To complete the regulatory requirements for recovering tyres from waste to products, a certification scheme is required in order to provide independent certification that producers are complying with...
the quality protocol and the PAS. WRAP commissioned C4S to develop and set up the scheme; this work took place during 2009, and the certification scheme and quality protocol were formally launched at a seminar in Birmingham on 3 November.

Further information on our certification services can be found starting on p. 43 of this Review.

During 2009, we have continued to work with HA to increase the incorporation of sustainability into their procedures. Work has included development of a standard template for site waste management plans for HA projects, and an Interim Advice Note on how this should be implemented on different types of project, e.g. new construction and maintenance. We have liaised with different areas within HA to bring all the various strands of sustainability together into the Project Control Framework (PCF), existing whole-life cost models such as Software for Whole-life Economic Evaluation of Pavements (SWEEP), and value management procedures for renewal works.

We have assisted WRAP with outreach to local authorities by carrying out a number of in-house seminars on the use of site waste management plans in order to incorporate sustainability into their projects. We have also assisted WRAP in developing guidance specifically for the civil engineering sector. We produced a guidance document on Designing out waste in civil engineering projects, which covers a wide range of project types including airports, highways, rail facilities, utilities, flood defence, power generation and the regeneration of brownfield sites. It is anticipated that the guide will be published in 2010.

As sustainability, and the carbon agenda in particular, become more important, we will continue to work with clients and others to develop systems and guidance that ensure that innovative solutions deliver genuine improvements in sustainability and do not compromise the performance of the construction.

Informing sustainable construction using life-cycle approaches
TRL has further enhanced its experience in the field of Life Cycle Assessment (LCA), and has streamlined LCA approaches such as “carbon footprinting” during 2009. In July, a review of the LCA of solid waste materials in highway construction was published. The study looked at using recovered materials from municipal waste (glass, plastic and tyres), and, using LCA, specifically investigated the environmental credentials of a system which incorporated glass as an aggregate replacement in asphalt. A carbon footprinting exercise was undertaken which investigated the contribution to climate change of a warm asphalt mix containing sulphur-enhanced bitumen relative to a conventional hot mix. TRL has also commenced work in 2009 with European partners, under the Framework Programme 7 (FP7), to optimise recycling levels of reclaimed asphalt. TRL leads the LCA element of this project.
Transportation

Our work in transportation involves the movement of people and goods, and we apply a broad range of diverse technologies to transportation systems in order to promote smart, safe and clean mobility. The range of technologies involved includes sensors, control systems and communications, and cuts across disciplines including engineering, telecommunications, computer science, finance, electronic commerce and vehicle manufacturing. Behavioural issues and human factors are also significant considerations. We mostly deal with roads, although recent work has involved the rail mode and surface applications within airports.

Our customers are mainly government-based organisations and the European Commission (EC). However, the number of customers from the commercial sector is growing and we increasingly work in partnership to deliver effective and efficient transport solutions. We also have a software group which, as well as providing research and consultancy services, has a developing and international business in the sale of transportation-related software.

We manage a range of equipment and facilities in our work, including car and truck driving simulators that are used to measure and improve driver performance as well as for other research studies involving the driver, the vehicle and the road environment.

During 2009, we further developed our work in the Middle East from offices in Dubai, Bahrain and a newly established office at the Qatar Science and Technology Park. Middle East customers typically place a high value on the science element of our consultancy and research services, and are ready to commission adventurous and intellectually challenging work, so we expect to see a growing share of our science activities in the region.
Research highlights: Transportation

During 2009, we undertook an internally funded study of the application of new algorithmic approaches to mathematical optimisation in traffic control. These approaches may have applications in a number of our software packages, including the TRANSYT signal optimiser. In another internal project, we investigated how TRL’s algorithms describing roundabouts could contribute to developments in microsimulation modelling of traffic more generally.

As well as continuing development of the SCOOT7 urban traffic control software, including bus priority measures (mostly in collaboration with TfL), we also continued to work with Imperial College London and Southampton University to develop concepts for urban traffic control up to 2050. We also developed links with other university partners, and have submitted two applications for Research Council funding under its Sustainable Urban Environment programme.

NETWORKS

The research undertaken on network performance focuses on improving our understanding of inter-urban traffic, supporting technological evolution, maximising network management interventions and honing network performance measures. Our expertise includes analysis, software modelling, operational research, technical consultancy and trials. During the year, a major summary report on motorway speeds and flows was produced[1 13] and another summarising work on the management and impact of abnormal loads[114].

We have continued to provide expert analytical support to our long-term clients during 2009. This has included work on the Highways Agency TRaffic Information System (HATRIS) and new journey time reliability measures. We have expanded use of our diagnostic tool Online Motorway Traffic Viewer (MTV), which enables visualisation of traffic conditions from buried road loop data, to include many more motorway links. In addition, our

TRAFFIC SOFTWARE

Our software mainly consists of traffic engineering products such as design tools for roundabouts (ARCADY), major/minor junctions (PICADY), isolated signals (OSCADY) and linked signals (TRANSYT). TRL software also supports online optimisation of individual traffic signals (MOVA) and linked signals (SCOOT). In addition, the Pedestrian Environment Review System (PERS) supports rapid and systematic assessment of pedestrian facilities in urban areas (see also p. 24 of this Review).

During 2009, we continued to develop TRL’s software. For example, we completed an updated version of ARCADY with added functionality including “level of service” indicators. We also developed PERS 3 with new Geographic Information System (GIS) capability and reporting functionality and, following the release last year of TRANSYT 13, which contains an explicit spatial representation of roads, 2009 saw the release of TRANSYT 13.1 with additional functionality, including TRANSYT 7f import and level of service indicators.

The Forward Thinking Award for innovation was won by TRL for its TRANSYT to VISSIM interface at the Intelligent Transport Systems (ITS) (UK) 2009 National Awards. This interface allows inclusion of the effects of traffic control on vehicle movements in significantly better fidelity than was hitherto possible in the VISSIM traffic model. During 2009, we continued to increase the integration of TRL software with other transportation products, including the Aimsun traffic modelling package.

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GPS TV software system supplements data from loops with GPS satellite-derived data from vehicles, enabling visualisation of traffic conditions on areas of the network where there are no loops available. This contributed to several key Highways Agency (HA) initiatives, such as the selection of sites for ramp metering trials. In an internal research project, the concepts of data fusion were investigated more widely, and it is anticipated that this understanding will be applied within GPS TV as well as allowing use of additional and more disparate data sources.

Our network specialists have further developed a signal simulation program to bring rigour and efficiency to developing Managed Motorway thresholds for triggering changes to speed and lane management options. We have also contributed to the development of innovative decision support tools for the West Midlands Urban Traffic Management Centre, and have been providing operational support to the Birmingham Box Managed Motorways roll-out. Such projects assist in optimising the benefit of the Government’s investment in highways technology.

During 2009, TRL further deployed the combined software–hardware system called DRUM[148], which enables roadworks contractors to effectively manage their road closures while minimising disruption to road users. The system was described in a paper presented at the Stockholm ITS Congress[133] and was honoured by being named as the Highway Industry Product of the Year at the Highways Magazine Excellence Awards 2009.

**INTELLIGENT TRANSPORT SYSTEMS (ITS)**

This aspect of our work focuses on the application of information and communication technology to transport, taking a system engineering view of vehicle–infrastructure interaction. Our ITS specialists provide research and consultancy services, technology procurement support and policy advice to government organisations (central and local, UK and abroad), and technology testing services to private industry. This is supported by our aviation specialists, who provide customer service benchmarking programmes for the airport community.

During 2009, we completed work on the Sentience Project, which was part-funded through InnovITS and the UK Department of Trade and Industry (DTI) – now the Department for Business, Innovation and Skills. In the course of this project, TRL worked with vehicle and system manufacturers to develop new fuel-saving strategies making use of environmental, traffic and vehicle information. A Ford Escape hybrid vehicle was fitted with the Sentience system, providing intelligent engine management based on externally transmitted information, and this was tested on the TRL large loop track and during pilot road trials. Results showed benefits with some of the fuel strategies during track tests. However, confounding factors, such as the interaction between the Sentience vehicle and other traffic, were found to mitigate some of the benefits during on-road tests but pointed to areas for further strategy development. There was much press interest in the project and the vehicle during the year (e.g.[147]).
The ITS Group often works in partnership with external organisations. For example, we continued to provide a “newsfeed” service to HA under the ITS-Radar Project concerning developments in ITS research, and in a study for the Department for Transport’s (DfT) Roads Liaison Group we worked with partners to compile a review of UK research organisations, subject areas and processes relevant to that group.

Work on cooperative systems (involving some communications between vehicles and the road infrastructure) formed a substantial part of the ITS Group’s work during 2009. On behalf of HA, TRL collaborated in the European project Cooperative Vehicle Infrastructure systems (CVIS), looking particularly at interoperability of on-board equipment between European test sites. Additionally, in work for the European Commission (EC), TRL provided an expert review of another major cooperative project, COOPERS. Many other projects, including those described below, involved some degree of vehicle/infrastructure communication.

During 2009, the ITS Group again worked on road pricing, tackling the difficult area of product/system certification and the challenge of verifying that charging systems are working correctly. TRL also became a partner in the European project GINA – Global Navigation Satellite Systems (GNSS) for INnovative road Applications, which is an EC co-funded project addressing the adoption of satellite-based charging in the road sector. The project is investigating large-scale technical feasibility, economic viability and impacts such as congestion and pollution.

In another charging project, sponsored by the UK Technology Strategy Board, TRL joined a consortium developing Third Generation RoadSide Equipment (3GRSE) using an innovative approach to implementing time/distance/place charging. This system uses existing roadside infrastructure. We also participated in organising and reporting on road pricing conferences at the Institution of Engineering and Technology in London and with the International Benefits Evaluation and Costs (IBEC) Working Group in Stockholm.

A significant European project during 2009 involved TRL’s leadership of a consortium to evaluate economic and deployment issues for an ITS system called “eCall”, which alerts emergency services to accidents and incidents on the road network. It may be automatically triggered, e.g. from an air bag deployment, or may be manually triggered by a driver or passenger, perhaps to alert the road authorities to a hazard on the carriageway. The system sends a digital message, including location, to the Public Service Answering Point (PSAP) and opens a voice channel to the vehicle. During the project, which involved four national case studies and a European-level analysis, the principal benefits were identified as safety related: rapidly alerting emergency services to the exact location of an accident allows quicker and more effective medical assistance. However, recent work in partnership with HA and within this project have, for the first time, identified and quantified the additional potential benefits for traffic management and congestion reduction.

Testing 3GRSE system on the TRL test track
THE MIDDLE EAST
During 2009, TRL delivered two projects to the Strategy and Governance Division of the Dubai Road Traffic Authority. The first investigated creative solutions to long-term commuting across Dubai, supported by extensive traffic modelling analysis to identify a set of parallel routes which could be upgraded as viable options to the main arterial roads. The second involved developing policy modelling tools for strategic analysis.

In Abu Dhabi we opened discussion with the Head of Civil Engineering at Abu Dhabi Men’s College, to support its new curriculum for a Bachelor of Transportation programme. This programme is being launched to train students sponsored by our client, the Abu Dhabi Department of Transport. We are also working with the department to deliver a three-year road safety strategy project and also working on a feasibility study to plan the introduction of a freeway service patrol to manage incidents and provide safety services to road users.

Part of the challenge of driving in the Middle East – in addition to the sheer weight of traffic – is driver behaviour. Building on the successes of safety projects in Abu Dhabi and Dubai, we are beginning to introduce licensing and driver training services, and are discussing the introduction of simulator-based training in 2010, in partnership with the Emirates Driving Company – one of the world’s most advanced driving schools.

In Qatar, Ashghal, the Department of Public Works, is an established customer and also operates a SCOOT system for traffic control. There, we have made several contributions to plans for a major initiative in ITS, including visits from senior TRL experts.

HUMAN FACTORS AND DRIVING SIMULATION
Our work in human factors and simulation focuses on examining the psychological and physical interactions between drivers, their vehicles and the driving environment. Our work is supported by state-of-the-art car and truck driving simulators. However, research work and expertise also encompasses TRL’s test track facilities and other specialist vehicles. Further details of the car and truck driving simulator facilities are given on pp. 13–14 of this Review.

Driver and information studies
During 2009, we produced a major report summarising previous TRL work on driver distraction from in-vehicle sources\(^{112}\), and continued to study the development of checklists as a rapid interface assessment tool.

In European work for the Department for Transport (DfT), we co-chaired an eSafety working group on Human Machine Interface (HMI) design and edited a report which will be put to member states supporting an EC mandate to further develop principles for design at a European level. As in previous years, we contributed to international standardisation (ISO) work on HMI, with a particular focus on standards for assessing driver visual demand and distraction.

Work began on a collaborative European project entitled INTERACTION, which aims to investigate how drivers interact with in-vehicle technologies in everyday driving situations, and how long-term use affects driver behaviour, performance and safety. As part of this research, TRL and European partners will be equipping cars belonging to participant drivers with sensors, in order to record their interactions with in-vehicle technologies as they go about their daily driving tasks. This “naturalistic” driving study will provide valuable insights into the use of such technologies during day-to-day driving, rather than by any direct experimental manipulation.
TRL is also participating in a novel European project called 2 BE SAFE, which aims to investigate behavioural and ergonomic factors that contribute to accidents involving powered two-wheelers. TRL has set up a databike facility, sponsored by North Yorkshire County Council. This is a Honda Fireblade motorcycle equipped with a high-specification data capture system capable of recording detailed information about vehicle performance and rider interaction with the controls. The motorcycle will be used to collect naturalistic riding data from participants.

Simulator studies (transportation)

The TRL car and truck simulators are used for a wide range of applications that relate to projects undertaken on transportation as well as safety and environmental issues. Some of the applications that are relevant and support our work in transportation are highlighted below. The applications that relate to safety and environment are covered on pp. 13–14 of this Review.

The HA research programme investigating driver behaviour in response to Managed Motorways and further use of the available infrastructure continued in 2009. These studies included:

- Emergency refuge area simulation[127]
- Through-junction running[116, 118]
- Dedicated lane studies[119]

The trials offer HA the opportunity to test changes that could help alleviate congestion, to ensure that drivers can use the new schemes intuitively and that the revisions do not compromise safety. TRL’s car driving simulator thus enables HA to make evidence-based decisions about the layout and design of road infrastructure before committing to any physical changes.

Further studies of the influence on driver performance of road layout have been carried out as part of an internal reinvestment project. In this particular study, we integrated a polysomnograph system with our car driving simulator to enable recording of a range of physiological measures including brain, heart, muscle, breathing and eye activity. This was then applied in a collaborative investigative study of driver workload and stress. This work is providing valuable information on the relationship between highway design and other factors affecting driver stress. Further information on this and related studies can be found on p. 14 of this Review.

Following award of the European Marie-Curie project, ADAPTATION, TRL is recruiting a PhD student to carry out research on responses to driver assistance systems, using TRL’s car driving simulator.
TRL actively supports both national and international institutions. It represents the UK Government on standards committees, and on European Union (EU) and United Nations (UN) working groups – such as that for the UN Economic Commission for Europe (UNECE). It also provides expert advice to a wide range of national and international organisations and committees. We provide editorial support to the boards of many technical journals, contribute to the organisation of conferences and seminars, and provide reviewers for research papers. We encourage close links with universities, both in terms of collaborating on research projects and providing support to the education process through lectures and the supervision and oversight of degree courses. We maintain close links with the professional institutions, and have accredited training schemes with the Institution of Civil Engineers (ICE) and the Institution of Mechanical Engineers. Some examples of these activities are provided below.

INSTITUTIONAL LINKS
National and international institutions
TRL continues as an active member of the professional organisation for Intelligent Transport Systems – ITS – (UK), where Alan Stevens is a member of the council and TRL staff frequently participate in the many task forces and interest groups. Tim Andrews is a member of the Technology Strategy Board’s Innovation Platform Steering Group. Bill Gillan serves on the transport panel of the Institution of Engineering and Technology. Kate Fuller serves as a member of the Institute of Highway Incorporated Engineers committee. Mike Winter is Chair of the editorial board of the Geological Society’s Quarterly Journal of Engineering Geology and Hydrogeology (QJEGH) and Murray Reid is on the editorial advisory panel of ICE that is responsible for the proceedings title on Waste and Resource Management. Alan Stevens is Editor-in-Chief of the journal Intelligent Transport Systems. This journal was awarded its first Impact Factor during 2009 and Alan was invited to continue as Editor-in-Chief for a further three-year term.

TRL continues to support international organisations, and is a member of the European Conference of Transport Research Institutes (ECTRI), Forum of European National Highway Research Laboratories (FEHRL) and Forum of European Road Safety Institutes (FERSI). It also participates in the activities of the World Road Association (PIARC) and European Road Transport Advisory Council (ERTRAC).

Sue Sharland and Bob Collis are members of the FEHRL General Assembly, Neil Paulley is a member of the ECTRI General Assembly and Andrew Parkes is a member of the FERSI General Assembly. Andrew is also a rapporteur of the ECTRI Working Group on Safety and Security, and Richard Woodward is a Research Coordinator for FEHRL. Iain Knight is a member of ERTRAC, with a special interest in HGVs. Alan Stevens is co-Chair of the eSafety Working Group on Human–Machine Interaction (HMI), which is preparing a report for member states on design

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8 An Impact Factor is a “figure of merit” awarded to a journal on the basis of the number of citations.
and safety issues with in-vehicle information systems. Paul Emmerson continued work during 2009 as a Commission for Integrated Transport (CfIT) Strategic Advisor on “Making Better Use of the Road Network” – in particular, on improving the acceptability of transport policies for road users.

Mike Winter is assisting Transport Scotland’s Chief Road Engineer and World Road Association UK First Delegate in his role as Chair of the World Road Association Strategic Planning Commission. Mike is also a member of the Strategic Planning Commission in his own right. The primary loci of the work of the commission are the monitoring of the technical committee activities, the development of the sessions’ themes for the World Road Congress in Mexico in 2011 and the development of the World Road Association Strategic Plan for the next four-year cycle. The last-named includes the development of briefs for the technical committees, the associated strategic themes and the other commissions, as well as undertaking a review of the World Road Association’s internal rules and statutes.

Members of TRL’s staff also sit on a number of PIARC committees. For example, Brian Ferne sits on technical committee D2, Road Pavements, and sub-committee D2a, Road Surface Characteristics; and Martin Lamb sits on the Terminology Committee.

TRL staff attend the annual Transportation Research Board (TRB) meeting and, for example, Mike Winter is a member of the TRB (US) Committee on Exploration and Classification of Earth Materials, an affiliate member of the Committee on Engineering Geology and a member of the technical committee for the International Society of Soil Mechanics and Ground Engineering’s (ISSMGE TC3) on the Geotechs of Pavements.

Standards committees
TRL is represented on several British (BSI), European (CEN) and International (ISO) Standards committees. For example, Cliff Nicholls sits on BSI B/S10/1 (Asphalt Products) and on the CEN/TC227/TC336 Ad Hoc Group on Adhesion, and is convenor of CEN/TC227/WG1/TG2 on Asphalt Test Methods. Phil Morgan is the convenor of CEN/TC226/WG6/TG1 (Noise Protection Barriers, Acoustical Task Group) and is a member of the British Standards Committee EH/001/02 (Transport Noise) and ISO Working Group ISO/TC43/SC1/WG33 (Measuring Method For Comparing Traffic Noise On Different Road Surfaces). Mike Ainge is a member of ISO/TC43/SC7/WG42 (Noise Emission from Road Vehicles) and BSI EH/1/12 (Transport Noise). Cyriel Diels attends ISO meetings on HMI and Alan Stevens is on the BSI Committee on ITS.

LINKS WITH UNIVERSITIES
Andrew Parkes is Visiting Professor of Life Sciences at Heriot-Watt University, Edinburgh. Alan Stevens joined an international panel of external assessors for an Engineering and Physical Sciences Research Council (EPSRC) event on “People in systems” research. This involved assessing work from UK universities in receipt of EPSRC funding and rating the research excellence before making overall comments on EPSRC’s programme. Richard Woodward sits on the Civil Engineering Advisory Board at Surrey University. We have started to work more closely with the University of Manchester, and staff in our Manchester office have agreed to meet on a regular basis with the Centre for Urban Regional Ecology (CURE), Manchester Architectural Research Centre (MARC) and Centre for Urban Policy Studies (CUPS) within the university. The aim is to combine the skills and expertise of the two organisations in order to develop joint projects. TRL is collaborating with Osaka University in Japan on regeneration of brownfield sites. Norika Otsuka attended the 9th Architectural Education Symposium in Tokyo in January, and Professor Nitta visited TRL in March to exchange research information on transport and climate change.

Richard Steele of Keele University was a visiting scientist at TRL during his academic sabbatical, and conducted a preliminary study on the effects of alcohol hangover on driving ability using the facilities of TRL’s car driving simulator. A European Commission (EC)-funded Marie Curie Research Training Network PhD student – Mazdak Ghajari from Imperial College London – was seconded to TRL for two months in order to use its crash test dummy and other facilities to validate his finite element (FE) computer model, as part of his research looking at the effect of the rest of the body on head impacts.

Tutoring and lecturing
Andrew Parkes was an external examiner for a PhD candidate at Brunel University. Alan Stevens acted as a PhD examiner at Imperial College London, and Mark Chattington acted as an examiner for an MPhil viva at Manchester Metropolitan University. Marianne Hynd is external academic supervisor of a PhD student at Surrey University. This studentship is part of the EU-funded Enabling Protection for Older Children (EPOCH) project.

Adam Giszczak presented a lecture at the University of Technology in Poznan, Poland, to students, university staff and guests from Poznan City Council. Nicholas Taylor undertook his annual CONTinuous TRaffic Assignment Model (CONTRAM) lecture to MSc students at the Transportation Research Group (TRG) of the University of Southampton. Andrew Parkes lectured to the Applied Psychology undergraduate course at Heriot-Watt University, Edinburgh, and to the Automotive Design undergraduate course at Coventry University.

TRL continues to run a number of courses as part of Surrey University’s MSc on Transport Planning and Practice. For this, we provide educational material, lectures and practical classes, and contribute to examinations. This year, there has been a particular focus on developing the courses for full distance-learning presentation.

Dinos Visvikis took part in the Engineering Celebration Day at the Royal Institution of Great Britain; the day was organised to complete the “Ingenious” project, which supported a group of young engineers in delivering a series of masterclasses to groups of 13–15 year olds. As part of the day, Dinos gave a short presentation on the aims and content of his masterclass, and demonstrated a hands-on experiment with the help of a couple of students. The presentation took place in the Faraday Theatre.
Research collaboration with universities
TRL has been working with a number of universities to develop ideas and submit research proposals. For example, an application has been submitted in partnership with Loughborough University under the EPSRC “Complexity” programme, and with Reading University, we have applied for a 12-week exploratory grant concerning new traffic sensors under the Knowledge Transfer Partnership (KTP) scheme. A number of outline applications have also been made following the EPSRC’s call for proposals under the Sustainable Urban Environment Programme. Other specific collaborations are under discussion with University College London, Imperial College London and the universities of Southampton and Bristol.

EDUCATION AND TRAINING
Following TRL’s appointment as an affiliated research centre of the Open University (OU), we are able to appoint, supervise and arrange viva examinations for PhD students – with degrees being awarded by the OU – and this year, we welcomed our first three students registered through this scheme. They are:

- **Tom Buckland**, who is studying methodologies that allow assessments of carbon and noise impacts in the development of national road maintenance programmes. This work is funded by the Irish National Roads Authority (NRA) as part of the OU Affiliated Research Centre scheme. His supervisors are Vijay Ramdas (TRL), Tony Parry and Andy Collop (both from Nottingham University).

- **Jo Carroll**, who is studying head injury mechanisms as part of the OU Affiliated Research Centre scheme. His supervisors are David Hynd (TRL) and Andrew Parkes (TRL).

- **Steve Skippon** from Shell, who is studying perceptions of vehicle performance with alternate fuels through the OU Affiliated Research Centre scheme. His supervisors are Nick Reed (TRL) and Andrew Parkes (TRL).

Other members of staff who are currently working for PhDs are:

- **David Richards**, who is registered for a PhD in the School of Engineering at the University of Cardiff. His subject is pedestrian kinematics in impacts with small city cars.

- **Alan Dunford**, who is registered for a PhD with the Department of Civil Engineering, Nottingham University, on the topic of the contactless measurement of skid resistance.

- **Dinos Visvikis**, who is registered for a PhD with the Accessibility Research Group at University College London on the topic of child safety in wheelchairs in vehicles.

- **Louise Walter**, who is registered for a PhD at the University of Southampton on the topic of graphical modelling of UK road accident databases.

- **Britta Lang**, who is registered for a PhD at Trinity College Dublin on the topic of drivers’ risk perception and capability as a function of age and experience.

- **Stuart McRobbie**, who is registered for a PhD in the Department of Civil Engineering at the University of Birmingham on the topic of new techniques for assessing the condition of highways structures.

In addition to our PhD students, there are several members of staff who are registered for MSc degrees or are pursuing chartered qualifications.

Several members of staff attended the “Young Researcher’s Seminar” in Turin on 3–5 June, which was organised jointly by ECTRi, FEHRL and FERSI. The event was intended to help participants develop skills in academic paper writing and presentation as well as networking. Michael Jenkins presented a paper on the calibration of the Traffic Speed Deflectometer, Helen Gibson presented her work on bus priority in urban traffic control systems, Rebecca Hutchins presented a paper on educational interventions to improve knowledge and understanding of safe driving in a prison setting, and Ryan Robbins presented work from the TRL car simulator on driver distraction. Neil Paulley was part of the organising committee, and Alan Stevens provided a keynote address and acted as a tutor to a group of young researchers.

A series of Vehicle and Operator Services Agency (VOSA) training courses was given in 2009. These courses deliver Cooperative Crash Injury Study (CCIS) training for examiners, and cover subjects such as the background and overview of crashes, the role of vehicle engineering, impact dynamics, data collection, occupant injury mechanisms and practical sessions on how to carry out full and correct examinations.

TRL STAFF AWARDS
During 2009, the Worshipful Company of Carmen awarded TRL the Herbert Crow Memorial Award, which honours individual academic, management systems or other contemporary knowledge-enhancing achievement. The award was made in recognition of the contribution that TRL’s research has made to improving safety, traffic flow, road construction and maintenance, and the environment over the last 75 years.

The TRL software team won the Forward Thinking Award for Innovation at the ITS (UK) 2009 National Awards. The award for innovation was won by TRL for the TRAFFIC Network Study Tool (TRANSYT) to VISSIM® interface. These programs are used extensively by traffic engineers and consultants, both in the UK and overseas. The new software provides a more realistic signals timing package. The prize was collected by Adam Giszczak, Principal ITS Consultant at TRL, at the ITS (UK)’s Presidents’ dinner.

9 VISSIM is a German acronym, “Verkehr In Städten – SIModelle”. It is a model for simulating traffic in cities and was developed by the German company PTV (Planung Transport Verkehr).
Research highlights: Institutional and professional development

**Peter Owlett** and a team of TRL researchers have been awarded the Highway Industry Product of the Year 2009 for DRUM. This is an innovative traffic management system for road works that is based on real-time traffic information, rather than rigid timetables.

**Mike Winter** has been awarded a citation by the City of Edinburgh and the Edinburgh Convention Bureau in recognition of his “…valuable contribution in promoting the city as a conference destination and raising the international status of Edinburgh in [his] professional field”.

**Cliff Nicholls**, a Freeman of the City of London, and **Ian Carswell** were awarded the Howard Medal by ICE in October 2009. The award is for the paper *Recycling surfacing materials back into thin surfacing systems* by Cliff, Ian, Daru Widyatmoko (Scott Wilson), Ric Elliott (SW), John Harris (Lafarge) and Richard Taylor (Shell). The paper was published in the August 2008 issue of *Construction Materials Proceedings of the Institution of Civil Engineers*, and has been nominated by the ICE Advisory Panel of *Construction Materials* as one of the best published in 2008. The paper has been now entered in ICE’s annual Awards-for-Papers Competition.

**Britta Lang** has been awarded the Christopher Bullock Award, which was established in memory of the former Institute of Advanced Motorists (IAM) Chief Executive who died in 2007. This special Prince Michael International Road Safety Award is made in association with the Institute of Advanced Motorists, and is accompanied by a one-off grant of £3500 towards research on driver behaviour.
CONFERENCES
TRL continues to be prominent in supporting conferences, not only by attending and presenting papers but also by sitting on scientific and technical organising committees. For example, Alan Stevens was co-organiser of the International Benefits Evaluation and Costs (IBEC) Road Pricing seminar in Stockholm, and participated in a European Programme meeting to select academic papers for the World ITS Congress. He was also appointed as Chair of the Programme Committee for the Road Transport Information and Control (RTIC) Conference taking place in 2010 in London, and served on the International Scientific Committee of the Driver Distraction and Inattention Conference that took place in Gothenburg.

Nicholas Taylor, Brian Lawton and Neil Paulley served on programme committees for the European Transport Conference. Richard Lambourn led the Publications Committee of, and Tony Read organised field demonstrations for, the Institute of Traffic Accident Investigators (ITAI) and Europäischen Vereinigung für Unfallforschung und Unfallanalyse (EVU) combined conference. Abs Dumbuya was again appointed to the Scientific Committee for the Driver Behaviour and Training Conference. Iain York, Marcus Jones and Sally Cairns were involved in the Planning and Transport, Research and Computation (PTRC) committees for the TPM (Transport Practitioners Meeting) and the Traffic Management Conference.

The ITS World Congress took place in Stockholm in September, and TRL was well represented: TRL staff chaired several conference sessions, and there were presentations on driver distraction, environmental issues, road pricing and network management (two papers on the last-named). TRL also had a stand in the exhibition, and held numerous meetings with fellow researchers and clients.

During 2009, staff attended and gave presentations at many conferences and events including:

• 21st Enhanced Safety of Vehicles (ESV), Stuttgart, Germany
• Society of Automotive Engineers (SAE) Congress, Detroit, USA
• 88th Transportation Research Board Annual Meeting, Washington DC, USA
• 21st Congress of the International Traffic Medicine Association, The Hague
• Young Researchers Seminar, Turin, Italy
• “Fit to Drive” Conference, Tallinn, Estonia
• Visual Image Safety (VIMs) Conference 2009, Utrecht, The Netherlands
• 2nd Global Navigation Satellite Systems (GNSS) Vulnerabilities and Solutions Conference, Baska, Krk Island, Croatia
• 1st International Conference on Driver Distraction and Inattention, Goteborg, Sweden


• “Driving Simulation in Training” Conference, Thessaloniki, Greece

• Transport Simulation Systems (TSS) User Conference, Barcelona, Spain

• “Human factors”, Europe Chapter, Conference, Linköping, Sweden

• Driver Behaviour and Training Conference, Amsterdam, The Netherlands

• Human Centred Infrastructure Design Conference, Naples, Italy

• Motorcycle Safety Conference, Berne, Switzerland

• International Conference on Road Safety and Simulation, Paris, France

• European Transport Conference, Leeuwenhorst, The Netherlands

• Human Factors and Ergonomics Society (Europe) Annual Meeting, Linköping, Sweden

• 4th International Conference in Driver Behaviour and Training, Amsterdam, The Netherlands

• 7th International Réunion Internationale des Laboratoires et Experts des Matériaux, Systèmes de Construction et Ouvrages (RILEM) Symposium on Advanced Testing and Characterisation of Bituminous Materials, Rhodes, Greece

• 17th International Conference on Soil Mechanics and Geotechnical Engineering, Alexandria, Egypt

• CABERNET 2009: 3rd International Conference on Managing Urban Land, St-Étienne, France

• “Walk21” Conference, New York, USA

• 8th International Conference on the Bearing Capacity of Roads, Railways and Airfields, University of Illinois, Champaign, USA

• Landslide Management in Mountainous Urban Areas Conference, Busan, Republic of Korea

• Second International Conference on Environmentally Friendly Roads (ENVIROAD), Warsaw, Poland

• Transport and Air Pollution 2009 Conference, Toulouse, France

• Institution of Civil Engineers meetings, London, England

• Institute of Highways and Transportation meetings, London, England

• Terrafuture Conference, London, England

• Department for Transport, Behavioural Studies Seminar, Horsley, England

• ITS Future Vision Conference, Portsmouth, England

• International Conference on Bio-mechanics of Injury (IRCOBI), York, England

• “Traffex” Conference, National Exhibition Centre, Birmingham, England

• Institute of Traffic Accident Investigators (ITAI) Conference, Hinkley, England

• MOVA Symposium, University of Hertfordshire, Hatfield, England

• LJMU 2009: 8th International Conference on Sustainable Aggregates, Asphalt Technology and Pavement Engineering, Liverpool John Moores University, Liverpool, England


• 2009 Jubilee Symposium on Polymer Grid Reinforcement, London, England


• Asphalt Industry Alliance (AIA) 2009 Asphalt Conference, “Carbon innovation ahead”, Coventry, England


• The Use of Geosynthetics in Flexible Paving Conference, Perth, Scotland

• 18th Annual Surveyor Winter Service Conference, “Cold comfort. The state of play”, Cardiff, Wales
Other conferences attended, but where TRL did not present a paper included:

- International Association of Public Transport (UITP) Congress, Brussels, Belgium
- North American 8th National Conference on Transportation Asset Management, “Putting the asset management pieces together”, Portland, USA
- 9th Architectural Education Symposium, Tokyo, Japan
- UK National Biomethane Conference, Loughborough University, Loughborough, England
- 8th Annual Surveyor Conference, Nottingham, England
- Infrastructure Asset Management Exchange, London, England
- Wales Waste Conference, Cardiff, Wales
- Crossrail Conference, London, England
- Asset Management for Highways Conference, Birmingham, England
- Road Surface Treatments Association Annual Conference, Coventry, England
- Annual Essential Highway Maintenance Conference, Northamton, England
Specialist consultancy services
The main purpose of TRL’s business is to carry out independent research aimed at providing knowledge-based solutions to the whole range of transport-related problems. One aspect of this work has been related to the development of standards, specifications, guidelines and protocols. As part of this process, we have been at the forefront of producing methods of testing products and processes, and have developed a comprehensive range of test equipment to support these developments. This equipment resource is constantly being updated as new areas of work are commenced. As a consequence, many of TRL’s facilities and the supporting expertise to manage them are unique and state-of-the-art. As such, they can be deployed in a broader sense to carry out more routine standard testing, certification and monitoring work as well as specialist “bespoke” commissions. As our customers have become more aware of this expertise and resource, the demand for these specialist consultancy services has grown rapidly and now forms a significant component of our business. We see this growth continuing and consequently, for the first time in our Annual Review, we have set aside a section devoted to highlighting just some of the services and consultancy support that we offer, which both complement and support our traditional research activities.

To provide a flavour of this aspect of our work, we have chosen to highlight three service areas that have grown rapidly in the last year. These are: product and standard testing; certification; and monitoring services. In addition, we have also included a brief description of the work of three of our internal support service areas which seldom get a mention in the Annual Review but nevertheless form a vitally important component in the work that we do. The internal services highlighted this year are engineering, the Library and Information Centre and our photographic services.
PRODUCT AND STANDARD TESTING
TRL has a long history of studying vehicle impacts and understanding how to test vehicles and vehicle components so that they provide improved protection when crashes occur. As a spin-off from this research, TRL has brought together its extensive safety testing facilities to establish a focused Product Testing Division, a source of world-class expertise and test facilities with accreditation to International Standard ISO 17025. This provides opportunities for customers to have their products tested to current standards but also enables a broader scope of services, which includes product development, certification and type approval.

Together with the main test areas mentioned below, the new Product Testing Division can provide extended value to both pre- and post-test scenarios. This includes the design of test programmes, the commissioning and analysis of results, and general support throughout via our consultancy and advisory services. Areas covered include site audits, accident replication and product solutions. In addition, co-operation through external strategic alliances have provided extensions in the Product Testing Division for the manufacture and sale of specific products.

Child safety product testing
As part of the Product Testing Division, TRL has established a Child Safety Centre which provides type approval testing to ECE Regulation 44 standard as a technical service for the UK approval authority, the Vehicle Certification Agency (VCA), as well as the Rijksdienst voor Wegverkeer (RDW) for the Netherlands Ministry of Transport. TRL has also attained approval this year from RDW to complete site audits as part of the Conformity of Production requirements for child seat manufacturers.

In 2009, TRL launched its new five-star rating scheme for child restraint systems. The rating scheme will clearly present individual products’ safety and usability performance to the market, and is supported by retailers and the Automobile Association (AA). The star rating is based on a suite of tests which assess the front- and side-impact performance and the usability of the product. This scheme will provide consumers with rigorous and independent performance ratings for all child restraint systems tested, enabling them to make comparisons and informed decisions on which product best meets their requirements.
Mobility safety products
Wheelchair testing is a major focus for TRL's Mobility Safety Centre. A new test bench and TRL's own-design surrogate wheelchair test piece have recently been introduced. Testing regulations and standards have not kept pace with the development of newly styled and powered wheelchairs. The introduction of this new test equipment will enable TRL to provide research opportunities which will develop new standards and assist manufacturers in the development and safety of their products.

Motorsport safety products
TRL's Motor Sport Safety Centre, a Fédération Internationale de l'Automobile (FIA)-approved laboratory, has introduced two new test rigs to support Formula 1 development and certification testing. Since motorsport components tend to be very specialised and expensive, the usual forms of destructive testing can be very costly in terms of collateral damage to components not directly involved in the test. To provide a more cost-efficient form of testing, while maintaining technical integrity, TRL's Engineering Services Team has designed the new test rigs to focus on the component under test while protecting other key, and expensive, components. This targeted approach is proving to be highly attractive to our customers in the motorsport industry.

Lightweight sled for go-kart testing

As part of the development of the Motor Sport Safety Centre, we are introducing a new “lightweight sled” facility to support a demand for the testing of go-karts. Under accreditation of the Commission Internationale de Karting (CIK), we will shortly be offering both development and certification testing.

Safety helmet testing
TRL's involvement in consumer test programmes encompasses motorcycle helmet safety. Through the Department for Transport's (DfT) Safety Helmet Assessment and Rating Programme (SHARP), motorcycle helmets are tested and rated against performance benchmarks. The test equipment primarily used for helmet safety testing is the TRL-designed Drop Tower Facility. This test rig includes a drop tower in excess of 15.5 m tall. The tower is capable of accelerating objects by gravity up to around 17 metres per second (63 kph) in either a guided or “free-fall” configuration. Impact performance is assessed by precisely guiding test samples onto a variety of impact anvils. Apart from providing a certification testing service, the facility is also used to help manufacturers develop suitable products prior to SHARP certification testing. It is also being used for research and homologation testing of other types of energy-absorbing structures as well as specialist safety helmets worn for other purposes, such as horse riding, industrial use and motorsports.

Drop testing a motorsport helmet

Security and vehicle restraint systems
The established Security and Vehicle Restraint Systems Team has met strong demand for the testing of security barriers and roadside furniture. Testing can be carried out in accordance with all major international standards, including PAS 68, ASTM, EN 1317, NCHRP350 and EN 12767. During 2009, TRL implemented a significant upgrade on the full-scale crash facility to accommodate the different (higher impact energy) test regimes needed for security systems. Apart from the testing of products and components, TRL can now offer a full design and consultancy service for security and vehicle restraint systems. This covers site threat and safety assessment, product design, testing and post-installation auditing, and installation advice.
In the mid-1990s, TRL and DfT were instrumental in developing a consumer testing programme for vehicle crashworthiness and safety. This programme, UK NCAP, was the forerunner of the corresponding European test programme, Euro NCAP. The vehicle impact testing conducted on behalf of Euro NCAP encompasses frontal impact with a 40% offset at 64 kph, which represents a vehicle-to-vehicle frontal collision; a side impact at 50 kph, also representing a vehicle-to-vehicle impact; and side pole impact, which represents a vehicle collision with a tree or roadside furniture. For each crash test, the vehicles are fitted with state-of-the-art data recording equipment and crash test dummies.

In addition to the full-scale vehicle impact tests, TRL conducts pedestrian impact tests. These tests include headform and legforms striking the front of a vehicle to assess the vehicle’s passive safety performance offered to pedestrians and other vulnerable road users.

Following the crash tests, TRL inspects and analyses the performance of the vehicles and provides expert interpretation as to the potential real-world risks, taking into consideration the effects on smaller and larger vehicle occupants when compared with the results for the crash dummies. Assessments are also made on the safety provided to child occupants and the recommended restraint systems used.
C&A is currently developing a number of schemes, which will address the technical and commercial needs of a variety of industries. These can be delivered under the TRL certification name, Certification & Assurance, or other industry bodies' names, i.e. by TRL operating bespoke certifications on behalf of others.

The certification initiative has been progressing steadily, and has built good industry contacts to help it develop potential certification schemes. It is assisting TRL’s researchers with developing their own certification-related work, and they in turn are increasingly supporting the initiative as an additional service in their own business offers.

It is worth noting that Euro NCAP has been a major success story in terms of driving forward improvements in vehicle safety standards. Since the first launch of results in 1997, over 300 vehicle models have been tested. Motor manufacturers have used Euro NCAP as a catalyst for initiating secondary safety improvements. These improvements, along with greater consumer awareness, have largely contributed to safer vehicles on European roads and ultimately led to a reduction in road deaths and serious injuries. Independent research by the Safety Rating Advisory Committee found that serious injury risk is reduced by approximately 12.5% for every Euro NCAP star. To date, TRL retains its position as the UK’s only accredited laboratory for Euro NCAP testing; this position has been further enhanced by the promotion of TRL employee Steve Adams to Lead Inspector for EuroNCAP. Steve travels the world on behalf of Euro NCAP to complete post-test inspections. This is a highly respected role, and has led to new opportunities of pre-NCAP test work with new overseas customers.

CERTIFICATION AND ASSURANCE

Certification is a way of showing that a company can assure the market of the ongoing compliance or performance of its products and services with standards or legal requirements. Rather than the use of a test report, which only shows the results of a test “on the day”, certification brings added value to the customer and to other market “drivers” such as a regulator, specifier or insurer. Certification schemes, therefore, are either legislative or created by industry and stakeholders through consensus for the good of their market. TRL certification programmes are created with this in mind.

As a result of the increasing demands from our customers, TRL’s certification business has grown rapidly and has reached a point where it made sense to bring together the various strands of this business under a single banner. This resulted in the setting up of a new subsidiary company during the latter half of 2008. The new company, Certification & Assurance Limited (C&A), is now operating as an independent certification body in both TRL’s traditional areas of work, and in new markets for customers who require a recognisable certification scheme for their products or services.

Our objectives have been to identify and build on either TRL’s existing activities, which can be seen as “quasi certification”, or situations where our reports and name are used by clients to gain recognition or acceptance in their markets. For example, TRL is now a notified body “test house” for safety restraint barriers and cushions to British Standard BS EN 1317, enabling both CE marking and acceptance on the Highways Agency’s (HA) approved products lists. Other examples include helmets, child restraints, recycled materials, road pavement materials, construction products and pavement testing equipment such as the Sideway-force Coefficient Routine Investigation Machine (SCRIM). As mentioned earlier, in motorsport we are an FIA-approved test house carrying out development and FIA compliance tests for Formula 1 teams and other FIA formulas.

This year, we have also started to build a business in certification scheme writing for other organisations. Some of these schemes are operated by a number of certification bodies, and some are bespoke for our own operation, as follows:

| TRACS and SCANNER1 survey contractors receive their accreditation certificates from TRL |

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1 TRACS = TRAffic-speed Condition Surveys; SCANNER = Surface Condition Assessment for the National NEtwork of Roads.
TRL’s reputation carries a lot of weight with major specifiers, and in pressured markets – where competition is intense – a robust and recognisable certification can make the difference between having a product or service selected or rejected.

**MONITORING**

**Emissions and air pollution**
TRL has been working with local authorities, a range of government departments and consultants since the early 1970s. While the focus of this early work was on research into monitoring approaches, sources and trends, this has been extended to provide consultative services in the area of transport emissions, fuel consumption, air quality and associated impact assessment.

**Recycled aggregates**
Thames Water has specified certification to TRL’s quality assurance-based scheme for recycled aggregates suppliers, as a prerequisite for companies hoping to be included on its approved supplier list. It is hoped that this scheme will later be extended to other utilities nationally.

**Certified rating scheme for child seats**
TRL has recently launched a new independent five-star rating scheme for child restraint systems, which has the support of several major retailers as well as AA (see also “Child safety product testing” on p. 45 of this Review). The new rating scheme provides rigorous and independent performance ratings for all seats tested, enabling consumers to make comparisons and informed decisions on which product best meets their requirements. Stars are awarded – from one star through to a maximum of five – and ratings will be publicly available on TRL’s web site (www.trl.co.uk/certification), which will hold all the latest information.

The market need for certification is very much driven by risk, and the need to reduce or optimise risk. As such, there are huge opportunities to expand certification activities both at home and overseas – and particular opportunities in the Middle East market for independent certified training courses and competence registers, for infrastructure contractors and road safety inspectors.

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**Creating an embankment with bales made from disused tyres**

**Child seat certification**

**Tyre recycling**
The Waste Recycling Action Programme (WRAP) commissioned TRL to write, and then own/operate, an industry certification scheme for companies who recycle tyres – by shredding or crumbing – for use in manufacturing other products, such as sports surfaces and pavements or walkways. The aim of this certification is to re-categorise the end result as “product” rather than as “waste item”. We are also, independently, writing a scheme for recyclers who produce tyre bales for civil engineering applications, such as embankments and reservoir substructures.

**Recycled aggregates**

**Certified rating scheme for child seats**

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**Roadside vehicle emissions checkpoint**
Current services include a vehicle exhaust emission remote-sensing system, which allows the measurement of emissions from individual vehicles without the need to stop and interfere with the traffic flow. Our team of roadside vehicle emission measurement testers also undertake vehicle emission (MoT) tests in compliance with the Road Traffic (Vehicle Emissions) (Fixed Penalty) Regulations 2001. These services have been widely deployed across the UK, and have been used to support a range of European projects.

We have continued to develop our in-house vehicle emission database, and TRL was responsible for the basic functions released in the 2001 and 2009 national emission factor releases. These data are used by our in-house emission modelling team, and also by government departments, including DfT and the Department for Environment, Food and Rural Affairs (Defra), local authorities and consultants. These data also form the basis for the road transport emission factors used in the UK National Atmospheric Emission Inventory. We have also developed emission modelling tools that are geared to the assessment of traffic management schemes, including Urban Traffic Management and Control (UTMC) applications and Managed Motorways. These tools are being applied to the assessment of air quality action plans, and general air pollution mitigation strategies.

Our Air Quality Monitoring Team provides a complete service from initial site selection and operation through to the collection, interpretation and reporting of results. The team is supported by our experienced and qualified engineers, who both install and service monitoring equipment. Our equipment includes a wide range of continuous monitoring systems that can be deployed to monitor gaseous and particulate matter at a wide variety of sites. The data from these systems are collected remotely, via GSM modems, by the Data Management Centre located at TRL. Here, the data are interrogated on a routine basis and are checked for quality and any operational anomalies. High-quality data capture is ensured through these routine data checks and instrument status inspections, and is backed up by a team of site engineers fully trained in the maintenance and calibration of the facilities. We also operate a site audit team that is routinely used to check and certify equipment and site performance. In addition to continuous monitoring, the team is able to offer non-continuous particulate monitoring and gaseous diffusion tube surveys.

One use of our expertise in emissions and air pollution monitoring is as data input into air pollution modelling and impact assessments. TRL has a long-standing reputation and significant experience in working with UK local authorities to fulfil their air quality review and assessment duties under the Local Air Quality Management (LAQM) Regime. The services offered include undertaking air quality monitoring and modelling review and assessments reports – including Updating and Screening Assessments (USA), Detailed Assessments (DAs) and Further Assessments (FAs), source apportionment studies, characterisation of emissions and scenario testing of action plan measures. TRL uses a range of dispersion models, such as ADMS-Roads, linked to MapInfo GIS software in order to undertake the majority of the modelling requirements for these reports.

The Air Quality Monitoring Team continues to develop its UK and international customer base, and has extended its remit to cover not only transport applications but also incinerator and biomass plants, airports, landfill sites, poultry units, steam railways, power generation and Combined Heat and Power (CHP) plants.
**Bridge integrity**

Corrosion of steel tendons in post-tensioned bridges can lead to fracture, compromising the strength and integrity of the bridge. The SoundPrint® acoustic monitoring system uses surface-mounted sensors to detect the acoustic energy released by the fracture of a wire and locate the position of the break. A laboratory trial conducted by TRL in 1998 provided independent verification that SoundPrint® was able to detect and locate wire fractures in steel tendons and cables, and to reject non-wire-break events. Following the laboratory trial, a field trial of the system was implemented at Huntingdon Railway Viaduct, Cambridgeshire. This proved so successful that TRL was commissioned to continue monitoring the structure using SoundPrint® for the long-term management of the viaduct; this monitoring is now in its twelfth year. TRL’s role is to install, maintain and manage the system, which incorporates acoustic sensors and data acquisition equipment, at the bridge, and to inform the client of any notifiable wire-break events detected by the system.

Demand for the SoundPrint® system has increased in the UK in recent years, and TRL is actively involved in its installation, maintenance and monitoring on three bridges in the UK – Huntingdon Railway Viaduct, Bowdon View Bridge and Thorley Lane Bridge – the last two being at junctions 7 and 5 of the M56, respectively. SoundPrint® provides non-destructive, continuous monitoring of these structures, and as part of a structural assessment package will save the bridge owners unnecessary repairs, traffic delay costs and premature decommissioning.

TRL is marketing the system to HA Area Managing Agents, the Welsh Assembly Government and Transport Scotland, as well as other bridge owners within the UK. We are currently in the initial stages of installing the system on a structure in the north-west of England, and are in early-stage discussions with other bridge owners/operators who have shown an interest in the use of the system as part of their management strategy for structures.

**Road condition**

Road monitoring techniques have been developed over a period of many years in order to provide highway engineers with an efficient means of assessing damage and deterioration to the road pavement, and to help identify appropriate maintenance treatments.

Initially, our work in this area focused on research to determine an in-depth understanding of the deterioration mechanisms for road pavements. This led to the development of measurement equipment, which, over a period of time, has evolved to the point where most assessments are now automated and can be carried out at traffic speed.
Much of the automated road condition monitoring work that we do is carried out on behalf of HA. This has delivered a range of benefits, including:

- Reducing the need for personnel to be on foot on the roadway and for disruptive road closures

- Facilitating the identification of potential maintenance schemes, budget planning and the production of performance indicators

- Providing a comprehensive understanding of current condition and performance

- Generating the engineering knowledge on which industry standards are based

Skid resistance was one of the first areas where automated measurement techniques were developed. In the 1970s, TRL pioneered the application of lasers to the automated measurement of road profile (texture depth, rut depth and ride quality). For example, the Highways Agency Road Research Information System (HARRIS), developed by TRL, was the prototype for traffic-speed surveys, which are now routinely used on a large proportion of the road network – namely, TRACS and SCANNER. There are now two HARRIS vehicles that are used for specialist surveys, providing Ordnance Survey grid references, road geometry (gradient, crossfall and curvature), longitudinal and transverse profile, texture profile, and forward and downward facing video and digital images of the road surface. The data from these systems provide a detailed understanding of road condition. A recent development of the HARRIS test vehicle is the installation of a device known as LIDAR (Light Detection and Ranging). This is an established, yet modern, technology that provides an image of the road and its surroundings. The system operates on the same principle as radar, but uses low-intensity lasers to provide a more detailed image. Three-dimensional images are created by spinning the laser emitter, which then provides 360° coverage. It is anticipated that, when fully operational, the LIDAR system will be used for a wide variety of purposes that include junction mapping, the detailed measurements of road architecture, the development of road infrastructure inventories and transport planning.
An exciting new development in traffic-speed surveys is the implementation in the UK of a Traffic Speed Deflectometer (TSD). The UK device was the second prototype created by Greenwood Engineering A/S and the Danish Road Institute and, after evaluation and development, started network surveys of the HA network in 2009. These will provide engineers with information on the structural condition of the road pavements. As routine deflectograph surveys of the trunk road network were discontinued in England in 2000, owing to the disruption caused by the slow speed of surveying, this will again provide the information on structural condition needed for maintenance planning and asset valuation.

While this development means that information on both structural and surface condition can now be obtained from routine traffic-speed surveys, there still remains an important role for the forensic investigation of pavements. Techniques including ground-penetrating radar, use of the falling weight deflectometer, coring and use of the dynamic cone penetrometer – all backed up by laboratory tests and expert interpretation – are still needed to establish the condition of the materials present and to determine the best form of maintenance intervention.

**Network performance and evaluation**

TRL has developed systems to support network performance management and to fine-tune traffic management systems. We use innovative techniques to reduce delays on the network, by ensuring that new traffic technology systems are optimised in their operation and that faults within the Motorway Incident Detection and Automatic Signalling (MIDAS) system are identified. For example, we are working in support of the South East Technology Managing Agent Contractors (TechMAC) in their role to look after the technology on the network in the south-east of England. Across the network, weekly “MIDAS health checks” are performed, which enable identification of any MIDAS loops that are likely to trigger incorrect or irrelevant signal behaviour. We also perform weekly checks on signals to identify spurious queue protection signals, allowing us to ask the Regional Control Centre (RCC) to disable the offending loop for high-occupancy settings (HIOCC) until it can be assessed.

Monitoring of the Managed Motorway section on the M25 is done on a daily basis, where we check for inappropriate signals or unusual traffic conditions using a TRL-hosted website called Online Motorway Traffic Viewer (MTV).

Constant monitoring of the signal settings on the M25 Managed Motorway takes place, enabling us to assess whether the signals are still consistent, coherent and appropriate for traffic conditions. If they are not, a review of the parameters is held in order to correct this.
As part of the development and operational support programme for the roll-out and installation of the West Midlands Urban Traffic Management Control (UTMC) Major Transport Scheme, TRL has been commissioned to undertake monitoring and evaluation of the delivery process and to provide strategy development and decision support tools. This major scheme aims to make more efficient use of the existing infrastructure and to reduce congestion on the network. The main objective of the monitoring and evaluation contract is to help the traffic and network operators in managing, monitoring and evaluating the impact of traffic signal operations on existing traffic conditions and to make better informed decisions about signal settings for future conditions, including incidents on roads and local or regional events. TRL’s role includes: developing micro-simulation models of UTMC areas; constructing a wide-area model to consider the impacts of incidents and events on the network; reviewing all existing models within the regions and identifying data and modelling gaps; evaluating the benefits of the scheme when operational; and engaging with the programme managers and end-users and their stakeholders.

**TRL LIBRARY AND INFORMATION CENTRE**

TRL’s Library and Information Centre is a unique information resource covering all aspects of transport research. All areas of land transport are covered including road, network and vehicle safety; traffic management; planning and control; pavements; structures; and geotechnics – plus environmental, technological and social issues concerned with transportation.

It has collections of published materials (spanning the last 60 years) in the form of books, periodicals, conference proceedings, standards, statistics, guidance notes and several thousand TRL Reports. In addition, it is building an impressive collection of electronic full-text documents, which includes a large number of TRL’s Reports as well as published reports from other transport research organisations.

Many major reference sources and key directories in the field are held in the Library. Full retrospective literature searches and monthly current awareness alerts can be provided on demand, using the Library’s in-house knowledge base. The knowledge base is a combination of library catalogue and the English language content of the International Transport Research Documentation (ITRD) database. TRL has a lead role in the administration of the ITRD scheme, which incorporates material from global sources as well as the UK.

The TRL “Current Topics in Transport” series is based on searches of this database. Membership of the ITRD system also provides valuable links to other transport research organisations around the world. These links give the TRL Library access to information in many other countries including the USA, Europe, Scandinavia and Australia. The Library and Information Centre also augments knowledge base searches with various online or Internet sources.

The TRL Library is not open to the public in the usual sense. However, visits for specific purposes can be arranged for a small fee. There are also various library membership packages available, which allow people to subscribe to a range of library services and publications according to need.
PHOTOGRAPHIC SERVICES
TRL’s photographic team undertakes all TRL’s stills and video work. This includes project support, marketing, advertising and general recording of what goes on at TRL. Facilities include a studio, video edit suite and preparation equipment, which enable a wide variety of work to be undertaken.

With the switch to digital imaging now all but complete, the world of photography has become more settled, at least so far as the technology is concerned. The recent changes in the world of business have, nevertheless, required the whole photographic industry to carry on evolving, ensuring that resources are tuned to maximise quality and workflow while keeping costs under control. Consequently, 2009 has seen improvements in efficiency but, nevertheless, a sustained output of high-quality work. Much effort has gone into updating TRL’s library of images, particularly those of TRL’s research vehicles. Examples of our work during the year include a “photo shoot” of HARRIS2 on the Grand Prix circuit at Silverstone, and action shots of the High-Speed Deflectometer on TRL’s own track. This has led to an interesting portfolio of unique photography. There has also been development work using infra-red imaging to examine compliance with mobile phone regulations by drivers.

During the summer months, stills photography was carried out: in London, in support of TRL’s security work; and in Liverpool, where passengers were photographed using the ferries, again in support of a research project. Another topic where photography played an important role examined the performance of a range of incident screens for use at the scene of crashes.

To strengthen our visual “brand”, TRL’s collection of high-quality images is steadily growing and the result of this is visible in the wide range of TRL’s publications, reports, publicity material and website. There is a long tradition of high-quality industrial photography at TRL, and this remains as strong as ever despite the technological and economic changes of the last few years.
ENGINEERING SERVICES
TRL has a highly skilled and experienced Engineering Services Team that provides engineering solutions for both internal and external customers. The team specialises in developing and maintaining new test rigs for the Product Testing Division, but also supports TRL research projects and the instrumentation of vehicles and components for testing. The team has also produced design and implementation solutions for external-barrier companies.

TRL’s impact sled facility is an in-house design, and the quality and performance of the facility has been recognised by external parties who want TRL to provide a replica system to aid development work through to homologation.

Developing a new rig for automotive component testing
This paper was first published in the Proceedings of Surf 2008, the 6th Symposium on Pavement Surface Characteristics, which was held in Portoroz, Slovenia, in 2008. The paper describes the research carried out under a programme of work on the automation of surface condition measurements funded by the Department for Transport.

**Dr Alex Wright** is an Academy Fellow who currently manages the Technology Development and Quality Assurance Group in TRL’s Infrastructure Division. While at TRL, Alex has led many projects applying new technology to the assessment and management of highway pavements and structures. This has included the design and construction of image- and laser-based high-speed condition monitoring systems, the development of novel processing and assessment methods, and the delivery of advice for highway engineers. Alex also leads TRL’s work in the quality assurance and accreditation of traffic-speed measurements systems, and is currently the quality auditor for all high-speed condition surveys carried out on the UK trunk and local road networks.

**Dr Helen Viner** joined TRL in 1997 following two years of post-doctoral research at the University of Nottingham. Helen leads a number of innovative research projects in the field of pavement surface characteristics, encompassing tyre-road interaction (friction, splash/spray and noise), accident trends, condition monitoring and performance indicators for pavement management. Helen has contributed to European projects on skid resistance and performance indicators, is a member of the TRB committee, “Surface properties – vehicle interaction”, and chaired the Technical Committee of the 2008 Conference on Safer Roads and Runways. Helen is an Academy Fellow, currently leads the Safety and Consultancy Group (which delivers a portfolio of projects for the Government, private sector and overseas clients) and has a strategic role in developing collaboration with universities.

**Andrew Gallagher** has a broad practical experience of research and the management of civil engineering projects. Andrew has held a number of senior management positions including TRL Head of Bridges Division and manager of the Highways Agency’s national research programme. Andrew was also the project manager on the Surface Condition Assessment for the National NEtwork of Roads (SCANNER) Implementation Project, working for the Halcrow Group. Andrew has many years of practical experience of highways asset management and civil engineering infrastructure research. He has designed and built roads and bridges in the West Indies, built sewers and sewage treatment works in north Wales, investigated structural concrete at the Cement and Concrete Association and managed research on the foundations of offshore structures and on radioactive waste depositories at the Building Research Establishment (BRE). Since April 2002, Andrew has been working as an independent consultant.

**Edward Bunting** has more than 25 years’ experience in Whitehall. He has worked in a number of departments and public bodies, with the last eight years spent in transport. His current responsibilities relate to policy on the management of local authority highways infrastructure, but before this he was part of the team that produced the ten-year Plan for Transport.
Developing the automatic measurement of surface condition on local roads
Alex Wright, Helen Viner, Andrew Gallagher and Edward Bunting

ABSTRACT: Following the successful application of traffic-speed surveys on the English motorway and trunk road network, the UK Department for Transport (DfT) has introduced traffic-speed surveys on the local road network in order to provide fully automatic measurement of their surface condition. By adapting technology originally developed for motorways, surveys of the local road network commenced on A-roads in 2005 and have since expanded to B and C class roads, now covering over 80 000 km of English classified roads each year. These surveys aim to meet the needs for national reporting of conditions, while providing data of value for local engineers. The task of meeting these dual goals required that suitable parameters be developed to identify the defects of key importance on local roads. A significant programme of research was commissioned by DfT to develop these. TRL provided a major input to this programme, carrying out research in several areas. Firstly, new parameters assessing ride quality have been developed that identify areas of most concern to the road user, in particular where there is localised roughness that causes vehicle jolting. Secondly, new parameters have been proposed that exploit the potential of texture and transverse-profile measurement systems in the measurement of surface deterioration across the full width of the pavement. Finally, a fully automatic method has been implemented that aims to identify deterioration, such as stepping and subsidence, developing at the outer edge of minor local roads. Each of these measures was assessed through comparison with conventional site surveys, and they have subsequently been implemented in the national survey of local roads.

1 INTRODUCTION
In the UK, automated traffic-speed surveys of pavement surface condition have been undertaken on the English motorway and trunk road network since 2000, under the TRAFFic-speed Condition Surveys (TRACS) contract. These surveys provide measurements of the level of rutting, cracking, ride quality and texture each year. The data is provided to highway engineers for use in the identification of lengths of the network requiring further investigation, prior to selecting appropriate maintenance treatments. In 2003, the Department for Transport (DfT) extended the application of automated carriageway condition surveys to local authority highways in England. This began with the introduction of TRACS Type Surveys (TTS) on principal roads in England in 2004, and then, from 2005, the Surface Condition Assessment for the National NETwork of Roads (SCANNER) survey\(^{(1)}\), which now covers local roads in England, Scotland and Wales.

Local roads differ from trunk roads because of their different types of construction, defects and maintenance. Because automated traffic-speed surveys were originally developed for the assessment of trunk roads, it was recognised\(^{(2)}\) that there was a need to develop new methods to process the survey data, in order to obtain condition parameters that could be used to identify the surface defects of importance on local roads. DfT therefore commissioned a programme of research to improve the capabilities of the SCANNER survey for the assessment of the surface condition of local roads. Key areas considered in this research programme included methods of assessing roughness and bumpiness using longitudinal profile data, the development of new approaches to measure surface deterioration using texture data, and the development of methods to identify and quantify deterioration at the road edge using transverse profile data. This last-named defect particularly affects narrower local roads.
2 MEASURING RIDE QUALITY ON LOCAL ROADS

2.1 Current approaches

TRACS and (at the commencement of this research) TTS and SCANNER survey vehicles provide measurements of the longitudinal profile of the pavement in the nearside wheelpath, at a longitudinal spacing of 100 mm. On local authority roads, the ride quality is assessed using moving average longitudinal profile variance. Moving average longitudinal profile variance is calculated by subtracting the value of the moving average filtered profile (over a defined length, L) from the longitudinal profile at each longitudinal profile point, and obtaining the square of this number:

\[ \text{Variance} = (P_j - P_jA)^2 \]  

where \( P_j \) is the profile amplitude at point \( j \), and \( P_jA \) is the moving average at point \( j \). Moving average longitudinal profile variance measurements are typically reported as average values over 10 m lengths. For the assessment of ride quality, three moving average longitudinal profile variance values are calculated. These are the 3 m, 10 m and 30 m moving average longitudinal profile variance values, which are generated using moving averages of length (L) 3 m, 10 m and 30 m respectively. These moving average lengths have been selected to represent different features of riding quality. The 3 m variance reflects the presence of small undulations in the road surface that may be more significant at lower speeds. In contrast, 30 m variance reflects the presence of long wavelength undulations (e.g. subsidence) that may affect ride quality at higher speeds. Previous work\(^\text{[3]}\) has shown that pavement profile features such as road geometry (i.e. crossfall, curvature, gradient) can cause higher values to be reported in the moving average longitudinal profile variance – particularly 30 m variance and, to a lesser extent, 10 m variance. Hence, a modified variance measurement, called "enhanced variance", has been proposed, in which the moving average is replaced by a filter of the profile data that reduces the contribution of long-wavelength features, such as road geometry, to the variance measurement\(^\text{[3]}\).

Other measures of ride quality are used in various countries. The International Roughness Index (IRI) measurement, extensively applied in the USA, simulates the response of a vehicle suspension system, and has a response that encompasses wavelengths ranging from less than 3 m to greater than 30 m in a single indicator\(^\text{[4]}\). Other measures – including Ride Number (RN), Profile Index (PI) and Half-car Ride Index (HRI) – are closely related to IRI. IRI is also used in Europe, along with other parameters that target specific wavelength ranges, such as the Coefficient de planéité 2.5 (CP 2.5), CP 10, CP 40, Short Wavelength Energy, Medium Wavelength Energy, Long Wavelength Energy, and Standard Deviation from 3 m, 10 m and 30 m moving averages. Many of these waveband-limited parameters can be correlated approximately to the UK measure of profile variance\(^\text{[5]}\).

2.2 Use of profile data on local roads

Before the introduction of the SCANNER survey, most local authorities relied on visual condition surveys to assess the condition of their roads, and were not familiar with the use of ride quality information in selecting lengths for maintenance. Discussions were held with a number of local authority and consulting engineers to assess their views on the value of ride quality information for maintenance planning. It was found that although ride quality had not been given a high priority in the assessment of pavement condition, its importance was increasing owing to its ability to reflect the users’ perceptions of the road network, and an increase in the responsiveness of local authorities to customer needs. Therefore, local authority engineers expressed a desire for reliable parameters that reported the general level of ride quality, and that also enabled them to identify locations where the ride would be deemed unacceptable (by the user) because of severe undulations.

2.3 Identifying suitable roughness parameters

To identify parameters that would assist in assessing the user’s perception of the ride quality, a programme of surveys was undertaken using instrumented vehicles to obtain a measure of user opinion in the areas of general ride quality and localised bumpiness. The vehicles included cars, a motorcycle and a bicycle. Quantitative information was obtained (from the car surveys) by providing the passenger with a dial and a push button, both connected to a data acquisition system (Figure 1). Users were asked to turn the dial to the position that related to their opinion of the general ride quality, and press the button when they considered the local level of bumpiness unacceptable. Several survey routes were completed, and the records of user opinion were compared with longitudinal profile measurements obtained using a SCANNER survey vehicle on those routes.

Figure 1: Data collection equipment for user perception surveys
Many parameters currently used for reporting ride quality are based on the assessment of particular waveband ranges. Hence, to assess the relevance of waveband-limited ride quality parameters, the profile data from the SCANNER survey were decomposed using wavelet analysis. The average of the (normalised amplitude) response to each wavelength for locations where the dial value was 2 or less was calculated and compared with the average of the (normalised amplitude) response to each wavelength for locations where the dial value was greater than 2. The process employed weighting so that (for example) locations where the dial value was 4 were given a larger weighting than those where the dial value was 3, in order to give a better representation of rougher roads. Figure 2 shows that the difference between the powers is greatest for wavelengths in the range 1–15 m, implying that wavelengths in this range cause users to experience discomfort. Further examination of the wavelet decomposition of the test data found that a large proportion of locations where the dial value was high corresponded to locations that only contained features with wavelengths less than 5 m. Furthermore, in the majority of the locations where the dial was high and there were features present in the range 5–10 m, features were also present that had wavelengths less than 5 m. Features with wavelengths greater than 10 m did not appear to have a significant effect on the opinion of the road users.

These user perception studies confirmed previous work\(^6, 7\) that the presence of short wavelength features gives rise to a general perception of poor ride quality in road users. Although features with wavelengths up to 10 m also contributed slightly to the user’s opinion, longer features (30 m) had little effect on our users.

Further tests were carried out to determine which ride quality measures would best reflect the user opinion. Given the agreement between many of the waveband-limited measures and similar correlation between different measures based upon IRI, the analysis was simplified by considering only IRI and a band-limited measure such as enhanced variance. Figure 3 shows the average enhanced variance and IRI measures obtained for lengths over which users reported the ride quality to lie within a range of 1 to 4 (no lengths were reported by the users with a value of 5). The standard deviations of the variance and IRI are also shown, which give an indication of the level of confidence that can be obtained in the figures. The general increase in variance with dial value (up to 3, with a flattening out at dial value of 4) suggests that we would have some confidence in the use of 3 m variance to report general ride quality. IRI also provides a reasonable indication of ride quality (in relation to user opinion). However, the higher standard deviation reduces the confidence in IRI, due to the higher probability of false positive/false negative reports of poor condition.

If we consider the increase in variance with dial value, and the relative proportion of the standard deviation of the variance, it can be seen that 10 m and 30 m variance show fair and little agreement with user opinion, respectively. Therefore, although 10 m variance could be used to assist in identifying lengths with poor ride quality, the large variation in the 30 m variance values suggest that this measure would not provide a significant improvement in the assessment of ride quality. These observations suggest that enhanced variance is a suitable measure for automated assessment of general ride quality, but that the reporting of 30 m variance is not necessary for assessing ride quality on local roads.

2.4 Assessing bumpiness

Our user perception surveys used both a dial, to record general perception of ride quality, and a push button, to identify individual jolts noticed by the road user. The button presses formed a discrete dataset of points corresponding to the locations where the users pressed the button on experiencing discomfort. Although it might be expected that locations containing bumps would correspond with the locations containing high levels of IRI or variance, it was found that only one-third of the locations where the 3 m variance was high (greater than the 95th percentile level) coincided with locations where the button was pressed. Hence, while variance appears to be a reasonable

<table>
<thead>
<tr>
<th>User opinion (dial value)</th>
<th>3 m enhanced variance</th>
<th>10 m enhanced variance</th>
<th>30 m enhanced variance</th>
<th>IRI</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1.73 ±2.31</td>
<td>5.15 ±15.8</td>
<td>46.43 ±113.3</td>
<td>3.44 ±2.80</td>
</tr>
<tr>
<td>2</td>
<td>2.77 ±2.96</td>
<td>9.18 ±22.6</td>
<td>81.52 ±238.2</td>
<td>4.63 ±3.49</td>
</tr>
<tr>
<td>3</td>
<td>4.62 ±3.28</td>
<td>16.32 ±21.7</td>
<td>123.6 ±184.4</td>
<td>6.01 ±6.10</td>
</tr>
<tr>
<td>4</td>
<td>4.49 ±1.65</td>
<td>13.74 ±12.0</td>
<td>133.2 ±65.1</td>
<td>5.91 ±5.26</td>
</tr>
</tbody>
</table>

Figure 3: Comparing the average values of different parameters with the user opinion (standard deviations in parentheses)
measure of general ride quality, it does not identify local features giving rise to bumps. The IRI has a similar deficiency.

Work was therefore undertaken to identify local profile defects (Figure 4) that would give rise to bumpiness to an extent that concerned the user. This work used the raw longitudinal profile provided by the SCANNER survey vehicle, and included analysis using Power Spectral Density (PSD) and wavelet techniques as well as bandwidth-limited profile parameters such as 1 m variance. However, the most promising results were obtained when considering the first and second derivatives of the raw profile, which was based on the premise that features causing a road user to report a jolt would be associated with a significant local change in the profile shape. Although the derivatives did respond to the presence of bump-like features, the measure was too sensitive. A method was needed to attenuate features less than 200 mm in length, corresponding approximately to the footprint of the vehicle tyre. The central difference method was proposed as an appropriate method. The derivatives for the Central Difference Method (CDM) are calculated as follows (for a set of raw profile measurements \( P_i \), measured at distances \( x_i \)):

\[
P'_i = \frac{P_{i+1} - P_{i-1}}{x_{i+1} - x_{i-1}}
\]

(2)

and

\[
P''_i = \frac{P'_{i+1} - P'_{i-1}}{x_{i+1} - x_{i-1}} = \frac{(P_{i+2} - P_{i-2}) (x_{i+1} - x_{i-1}) (x_{i+1} - x_{i-1})}{(x_{i+2} - x_{i}) (x_{i+1} - x_{i}) (x_{i-1} - x_{i-2})}
\]

(3)

In the approach implemented in SCANNER, the raw data are used to calculated \( P' \) and \( P'' \) for each data point. Then the maximum of both \( P' \) and \( P'' \) is calculated for each 1 m length, to gain two further parameters for each 1 m length: \( F' \) and \( F'' \). In order to identify bumps, thresholds are required for \( F' \) and \( F'' \). Where both \( F' \) and \( F'' \) exceed these thresholds, the 1 m length is considered to contain a bump. Clearly, the sensitivity of the bump measure depends on the thresholds set for \( F' \) and \( F'' \). The 95th, 97th, 98th, 99th and 99.5th percentiles were considered and the measure tested on several survey routes, comparing the reported bump measure with the results of the user surveys. Figure 5 summarises the results obtained on a 44 km local road test site located in central England.

<table>
<thead>
<tr>
<th>Threshold for ( F' )</th>
<th>Threshold for ( F'' )</th>
<th>Number of bumps reported</th>
<th>Number of button presses successfully detected</th>
</tr>
</thead>
<tbody>
<tr>
<td>&gt;99.5th%ile</td>
<td>99th%ile</td>
<td>793</td>
<td>48 (84% of total reported by user)</td>
</tr>
<tr>
<td>one-metre lengths (out of 44 000)</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**Figure 5:** Identification of bumps on a 44 km test site

It can be seen that the bump measure is able to detect most locations reported to contain a bump by the road user. However, this is at the expense of a large number of false positive reports of bumps. Inspection of the raw profile and video images of the sites found that, often, significant features were present at the locations where there were potential false positives. As network-level data are typically assessed over 10 m lengths, the final output of the “bump measure” is a report for each 10 m length, stating whether the lengths contained any bumps or not. In further testing, this measure was applied to survey data collected in the TRAFFIC-speed Condition Surveys (TRACS) of the road and motorway network in the south-east of England. A total of 10% of the bumps reported by the measure were randomly selected, and the 3D profile from the survey inspected. In addition, a site survey was carried out on 1% of the reported locations. The inspection of the 3D profile confirmed that 87% of the locations contained obvious bumps, with a further 10% showing general unevenness. Of the locations visually inspected on site, over 85% were confirmed as accurate reporting of bumps (60% related to bumps in the pavement surface owing to defect, and a further 24% were associated with poor bridge joints).

A separate study showed that locations with high values of the bump measure were also prone to generating body rattle noise as a result of the high vertical accelerations produced in vehicle suspension systems. Since body rattle noise can be a more important cause of nuisance or disturbance than tyre noise in urban areas, the bump measure could provide engineers with a useful means of assessing noise nuisance problems.

### 3 USING TEXTURE TO ASSESS SURFACE DETERIORATION ON LOCAL ROADS

#### 3.1 Current use of texture data on local roads

Before this research, TRACS and SCANNER survey vehicles provided measurements of the texture profile of the pavement in the nearside wheelpath. These data are provided at longitudinal intervals of 1 mm. On both the trunk and local roads, the data is processed to obtain the Sensor Measured Texture Depth (SMTD). SMTD is a Root Mean Square (RMS) measure of the texture both above and below the mean level (in contrast to Mean Profile Depth, MPD, which measures the height of peaks above the mean level). The SMTD values are calculated over 300 mm lengths, and then reported as average values over 10 m lengths for delivery to the engineer in assessing pavement condition.
The texture depth provides an assessment of the water shedding capability of the pavement, which is an important property for the achievement of high-speed skid resistance. Currently, the SMTD data are compared with thresholds established for maintaining texture on roads carrying high-speed traffic, in order to maintain adequate friction in wet conditions. Analysis of a sample of typical data on A-class (main) roads showed that it would be realistic to apply similar thresholds to these roads, which carry high volumes of traffic at high speeds. However, applying simple thresholds to data collected in the nearside of B and C (minor) roads was less straightforward, because of the high proportion of these roads with relatively low texture and the fact that the sections that engineers identified with surface texture defects did not, typically, exhibit particularly low texture. Therefore, we investigated whether texture measurements could be used as an adequate surrogate for skid resistance, and sought to develop alternative approaches to detecting defects in the surface texture.

3.2 Texture as a surrogate for skid resistance measurements

Because skid resistance measurements, using systems such as the Sideway-force Coefficient Routine Investigation Machine (SCRIM), are carried out separately from SCANNER surveys, it would be desirable to be able to use texture data as a surrogate for (low-speed) skid resistance. Work was therefore undertaken on a number of local road test sites to explore the feasibility of this by comparing SCRIM data, expressed as the Mean Summer SCRIM Coefficient (MSSC, a measure representing the typical friction measured at high slip speeds, for which the texture depth is important, and friction measured at low slip speeds, using devices such as the SCRIM and GripTester, which is largely determined by other properties of the pavement surface.

A second part of the study compared the lengths of an urban road network below skid resistance thresholds with the lengths that were below a texture-depth threshold. This also showed that there was little overlap between the lengths identified by the two measures.

These findings confirmed the distinction between friction measured at high slip speeds, for which the texture depth is important, and friction measured at low slip speeds, using devices such as the SCRIM and GripTester, which is largely determined by other properties of the pavement surface.

3.3 Enhancing the use of texture data on local roads

Although it is not feasible to use SCANNER texture data as a direct measure of skid resistance, it was felt that it should be possible to use texture-depth measurements to measure the surface deterioration associated with changes in surface texture. Such deterioration includes defects such as fretting (where aggregate is lost from the surface of the pavement) and fatting up (where the aggregate becomes embedded in the surface of the pavement, and hence covered in binder). Consultation with local authority engineers found that they were keen to obtain a measure which highlighted the likely presence of such defects.

Some SCANNER-accredited survey vehicles measure the road profile using lasers mounted transversely in at least 20 measurement positions. Currently, the transverse profile is reported every 100 mm, but the lasers sample at a much higher rate than this and are, potentially, capable of providing information on the surface texture. To assess the potential of existing systems to provide texture data across the whole lane width, bespoke data collection software was employed on the Highways Agency’s (HA) HARRIS1 survey vehicle[9], to obtain measurements at longitudinal intervals of approximately 5 mm. Note that at this sampling rate, the texture profiles had a reduced wavelength response in comparison with that provided by the standard single SCANNER texture laser, but a comparison of the data obtained from the two sources clearly indicated that the profile system provided sufficient sensitivity for the measurement of surface texture.

To assess this, values of SMTD were obtained every 1 m, for each of the 20 lines of texture profile, in order to provide a grid of surface texture data. An example of this grid is shown in Figure 7, where the individual SMTD measurements have been divided into three levels to obtain the orange (0.4–0.6 mm) and red (<0.4 mm) colour coding. It can be seen that this approach is able to highlight the presence of the road markings and surface deterioration.

The greater level of detail provided by the multiple lines of texture data improves the usefulness of these data for the identification of surface deterioration. In particular, the data allow us to assess the variability of the surface texture across the full width of the traffic lane. Since local roads can exhibit different levels of texture when in good condition, in many cases it is the variability rather than the absolute measure of texture that enables us to identify deterioration. For example, Figure 8 shows the variation in SMTD across the width of a road.
4 MEASURING EDGE DETERIORATION ON LOCAL ROADS

4.1 Current approaches

One of the most significant limitations in applying automated traffic-speed survey techniques to local roads was the inability to detect and measure edge deterioration. Edge deterioration is a widespread problem on local roads, particularly on narrower rural roads without edge support (e.g. kerbs), and local authority engineers have highlighted it as one of the main causes of pavement maintenance expenditure. There are two key aspects to this problem: deterioration of the pavement edge owing to inadequate foundations or lateral support; and deterioration of the verge caused by vehicle overrun, leading eventually to potholes adjacent to the carriageway. In the UK, surveys of edge deterioration are typically made using either Coarse or Detailed Visual Inspections (CVI or DVI). However, whereas DVI surveys are carried out on foot, CVI surveys are often carried out from a moving vehicle. Defects are reported as edge deterioration when “...occurring within 0.5 m of the road edge and not extending further than 0.5 m from the edge and extending right to the edge”[10]. Both CVI and DVI surveys assess the extent and severity of the deterioration. However, as the CVI survey is carried out at higher speed than DVI surveys, its level of detail is reduced.

4.2 Identifying edge deterioration using SCANNER

Discussions were held with a number of local authority engineers to assess their views on the use of SCANNER data to identify edge deterioration. Although current DVI manual surveys provide detailed information on the presence and extent of defects, engineers stated that their minimum requirement for the traffic survey would be a reliable but basic measure, indicating the presence of edge deterioration along a length of road. However, an individual edge defect of specific interest was that relating to the development of potholes at the road edge, which is a key defect related to road safety[11].

Although previous work had been carried out using highly detailed data collection and processing methods to identify and report the presence of edge deterioration[12], it was considered essential that the techniques for the automatic identification of edge deterioration should exploit the data already being delivered by the SCANNER survey. This would enable the rapid implementation of the methods contained in the network survey. It was proposed that the automated identification of edge deterioration would use the raw transverse profile data provided by SCANNER, which consists of a set of at least 20 transverse profile points spanning a transverse width of up to 4 m of the traffic lane, delivered at a longitudinal spacing of 100 mm. This data can be plotted along the road, as shown in Figure 4.

Visual examination of SCANNER transverse profile data collected on a selection of local road sites showed that on narrower roads, typical of those displaying edge deterioration, the transverse profile measurements typically extended over the edge of the carriageway, and the transverse and longitudinal undulations in the road surface associated with edge deterioration (resulting from deformations, potholes and breaking up of the surface at
the edge of the road) were visible within the transverse profile data. This led to the conclusion that it should be possible to identify edge deterioration by firstly identifying the position of the road edge in the data, and then applying appropriate analysis to the transverse profile data collected close to this edge boundary[11].

4.2.1 Identifying the road edge
Because SCANNER survey vehicles record the transverse profile outside the width of the survey vehicle (up to 4 m survey width), there is a significant probability on narrower local roads that transverse profile data will be collected which cover both the carriageway and the nearside verge. We cannot assume that the points reported in the extreme nearside of the transverse profile relate to those recorded at the edge of the paved road surface. Indeed, if these points have actually been recorded over the verge, which is likely to be uneven, there is a high risk that we would incorrectly report the presence of edge deterioration. Therefore, we need to identify the true edge of the road so that we can extract and assess the data that are correctly related to that road edge.

A method was developed to identify the road edge using a second derivative method, which locates any step or slope in the transverse profile data marking the edge of the road surface. The position of the road edge is determined from the average of all transverse profiles recorded in each 1 m length of the survey. Each transverse profile recorded within the 1 m length is then aligned with the average profile, and the road edge position is allocated to the individual profiles using the transverse shift value calculated when aligning to the averages[13]. This approach is based on the assumption that the position of the edge of an un-deteriorated road should change only gradually as you travel along the road, and therefore that the average profile should contain a better indication of the true road edge. Individual transverse profiles enable the identification of localised changes in the road edge (for example, those resulting from potholes at the road edge). Where the transverse profiles do not contain a clear road edge feature (e.g. because the SCANNER vehicle has not recorded over the edge of the carriageway), the edge position is placed at the nearside of the transverse profile. Once the road edge position is located for each transverse profile, a road edge region is defined, extending to a point 0.5 m to the right of the edge. This defines a road edge strip, which is used for calculating edge deterioration – see Figure 9.

4.2.2 Edge roughness
The edge roughness measure assesses the shape of the pavement in the region of the edge strip. Lines of longitudinal data are extracted from consecutive transverse profile points recorded in the edge strip. The 0.6 m moving average longitudinal profile variance (Equation 1; Figure 9) is calculated along each line, and reported at longitudinal intervals of 100 mm. The edge roughness value is obtained by calculating the mean longitudinal profile variance for 10 m lengths of road, using only those points that occur within the road edge strip (blue dots in Figure 9). Note that it is not a requirement of the SCANNER specification that transverse profile data be corrected for vehicle movement. However, it is required that the data be delivered without any normalisation, so that a component of 3D road shape information remains within the transverse profile data. The 0.6 m filter removes long-wavelength undulations, while capturing the local surface unevenness. Although the effect of severe or sharp bumps on the vehicle suspension might contribute to the output of this filter, these bumps are likely to be caused by the unevenness, potholes and bumps that this method is attempting to identify.

4.2.3 Edge stepping
Edge stepping defines the height of any step (up or down) in the transverse profile at the road edge. This is illustrated by the yellow ribbons in Figure 9. A line is fitted (by linear regression) to the transverse profile heights that lie between the road edge point and 1 m to the right of the edge point (into the road). This smooths the transverse slope of the road surface next to the road edge and prevents any severe crossfall exaggerating the edge step measurement. The height difference between the transverse profile points outside the edge of the carriageway is compared with the extrapolated road slope line, and the height of any step is established.

Figure 9: Defining the road edge strip for measuring edge deterioration
edge stepping value is reported over 10 m lengths as two edge stepping parameters. These indicate the percentage of the reporting length where there is a step down in height from the road surface to the “verge”. The two parameters report different sizes of step. Level 1 steps are between 20 mm and 50 mm; level 2 steps are greater than 50 mm.

4.2.1 Transverse variance – assessing unevenness across the road
The transverse variance parameter aims to further highlight the presence of edge deterioration by comparing the roughness of each half of the survey width, and is based on the assumption that a significant difference between the two halves is likely to indicate the presence of edge deterioration. In this method, the statistical variance of the profile height values is calculated for the left and right parts of the profile, either side of the vehicle centre line, following the removal of points to the left of the identified road edge. The difference between the variance of each half of the profile provides an indicator of the extent to which the roughness of any defects at the road edge exceeds the general roughness that would be expected across the whole carriageway (represented by the right-half variance). This is illustrated by the purple ribbons in Figure 9.

4.3 Assessing and using the SCANNER edge deterioration parameters
SCANNER surveys were undertaken on a range of sites located on the local road network, covering classified (A, B, C) and unclassified roads in both urban and rural areas. Data from Course Visual Inspection (CVI) surveys was also obtained on these routes in order to provide reference data against which to assess the SCANNER edge deterioration parameters. Initially, we compared individual parameters with results of the CVI survey to assess the capability of the individual parameters in identifying edge deterioration. Figure 10 compares the CVI data (plotted as the average severity obtained over the 1 km reporting length, to reduce noise in the data) with the reported intensity of edge stepping (here showing the number of 10 m lengths within each 1 km reporting interval for which edge stepping was reported). The comparison shows good agreement between the automated and manual techniques. However, note that CVI surveys simply report the total amount of edge deterioration present and not the individual edge defects making up the reported edge condition.

To meet the underlying need of local authority engineers (a basic measure of edge deterioration for individual lengths of road), we combined the individual parameters to obtain an overall indicator of edge condition, referred to as the edge deterioration indicator[14]. A single indicator reduces the burden on engineers for the assessment of survey data. The single indicator also enables better comparison with the single report of edge deterioration provided by current manual (CVI) surveys.

The SCANNER edge deterioration indicator combines the four SCANNER edge deterioration parameters (edge roughness, transverse variance, edge step level 1 and edge step level 2) for each 10 m length of pavement. Because these parameters have different relative intensities, it was necessary to normalise their outputs before combining them. The normalisation process assigns a score to each parameter, between zero and one, determined by the value of the parameter relative to two thresholds \(T_{lower}\) and \(T_{upper}\). Below \(T_{lower}\), the parameter is assigned a score of zero. Above \(T_{lower}\), the parameter score is increased linearly until the parameter value reaches \(T_{upper}\), above which the score is one. Values for \(T_{lower}\) and \(T_{upper}\) were based on observation of the behaviour of the parameters on a 200 km dataset. The normalised parameter values \(y\) were then combined using weightings to obtain an edge deterioration indicator, \(E\), having a value between 0 and 100:

\[
E = W_{edge\ roughness}y_{edge\ roughness} + W_{trans\ variance}y_{trans\ variance} + W_{edge\ step\ 1}y_{edge\ step\ 1} + W_{edge\ step\ 2}y_{edge\ step\ 2} \tag{4}
\]

Figure 10: Assessment of edge stepping – comparison with CVI data (edge step level 1 and 2) on 120 km of survey data from Hampshire and Leicestershire
The weighting values for each parameter ($W_r$, $W_v$, $W_E$, $W_{12}$) were obtained by considering how closely each parameter was related to the observed edge deterioration in the reference datasets. Note that the edge deterioration indicator can be calculated over any required reporting length by averaging the values reported for each 10 m length over the required reporting length.

Figure 11 compares the edge deterioration indicator with the results of manual surveys carried out on 120 km of our test dataset (the data has been summarised over 1 km lengths in order to simplify the comparison). It can be seen that the automated traffic-speed measure provides a good degree of agreement with the manual survey, although there are some lengths where the indicator reports the presence of edge deterioration that was not reported by the manual survey. Closer examination of the survey data over these lengths indicated that some deterioration was present but that the automated survey may have a higher level of sensitivity than the manual survey. This probably highlights a need for further “tuning” of the thresholds and weightings of the parameters used in the edge deterioration indicator.

Performance indicators are commonly used at network level to assess the overall condition of the network. In the UK, a typical approach is to calculate the total percentage of the network exceeding a defined level of condition. A threshold was defined for the edge deterioration indicator (30 points) above which it was considered that the level of deterioration was significant. The proportion of our test network exhibiting this level of edge deterioration was compared with the proportion of the network reported to contain edge deterioration in our manual reference surveys. We then sought to determine whether, at the network level, the traffic-speed automated techniques report similar proportions of the network to contain edge deterioration as the slow-speed manual techniques. Figure 12 presents the results of this analysis, broken down by road classification. Note that Figure 12 employs different scales for this comparison, in which absolute intensities are less relevant than trends. It can be seen that the relative proportions of the network exhibiting edge deterioration was significant. The proportion of our test network exhibiting this level of edge deterioration was compared with the proportion of the network reported to contain edge deterioration in our manual reference surveys. We then sought to determine whether, at the network level, the traffic-speed automated techniques report similar proportions of the network to contain edge deterioration as the slow-speed manual techniques. Figure 12 presents the results of this analysis, broken down by road classification. Note that Figure 12 employs different scales for this comparison, in which absolute intensities are less relevant than trends. It can be seen that the relative proportions of the road classifications reported to contain edge deterioration by the manual and automated methods are broadly similar and that, as would be expected, the extent of edge deterioration increases as the road classification decreases (from A to C).
5 CONCLUSIONS

As part of the introduction of automated traffic-speed surveys of road surface condition on local roads in the UK, there was a need to develop appropriate methods to process the survey data so that it could be used to identify surface defects relevant to the assessment of local roads. A programme of research has been undertaken that has developed methods to assess roughness and bumpiness using longitudinal profile data, surface deterioration using texture data, and edge deterioration using transverse profile data.

We have determined that 3 m and 10 m enhanced variance are suitable tools for the assessment of general ride quality that agrees with the user’s perception of the ride quality. We have found that there is little benefit in the use of 30 m enhanced variance for assessing users’ opinion of ride quality. However, parameters such as 3 m variance do not identify the bumps (such as potholes) that cause distress to the road user. We have therefore developed the central difference method to identify lengths where users experience jolts.

While current measures of texture depth are applied successfully to assist in the assessment of high-speed skid resistance (in combination with friction measurements), it would not be appropriate to attempt to use these data as a proxy for friction measurements. Nevertheless, there is potential for the use of texture data to identify surface deterioration on local roads. However, the successful application of this approach ideally requires the delivery of texture data at a higher level of detail than that traditionally provided by traffic-speed techniques. We have proposed the use of enhanced transverse profile measurements for this purpose, and shown that these data could be used to identify surface deterioration. However, there is a need for further development of this approach in order to relate the different patterns of surface texture to the condition of carriageways and the identification of defects.

Finally, the successful deployment on local roads of automated traffic-speed surveys, such as SCANNER in the UK, requires the delivery of parameters that identify the presence of edge deterioration, which is both significant and unique to local roads. It is possible to identify edge deterioration using transverse profile measurements obtained over the road/verge interface, and we have used this to develop measures of the unevenness and stepping that occurs at the road edge as a result of this defect.

All of the above developments have been implemented in the 2007/8 SCANNER survey of the UK local road network. Work is ongoing to refine these methods in the assessment of the condition and maintenance requirements of local roads in the UK.

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REFERENCES


This paper was first published in the Proceedings of the 21st International Technical Conference on the Enhanced Safety of Vehicles, which was held in Stuttgart in 2009. The research programme behind the paper is the Co-operative Crash Injury Study (CCIS – www.ukccis.org), Phase 8, which was funded by the UK’s Department for Transport, Autoliv, Ford Motor Company, Nissan Motor Company and Toyota Motor Europe.

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Rebecca Cookson joined TRL in 2006 after completing her Master’s degree in Physics at Durham University. She is currently a Researcher in the Crash Analysis Group, which is a role that involves analysing the various accident databases and fatal files held at TRL for a variety of research projects. Specifically, Rebecca has worked on a wide range of projects that include Topic Reports on stature and elderly occupants for CCIS, and research into injuries received in pedestrian accidents (using medical data, car occupant thorax injuries and linking offence history data to accidents) in the On The Spot (OTS) study. Rebecca also has extensive experience in the relation of damage measurements to impact speeds. She has published her work widely and made presentations at several conferences in Europe.

David Richards joined TRL in 2006 after graduating with a Master’s degree in Physics from Durham University. Since then, David has been working in the Crash Analysis Group. David’s main responsibility is analysis of the accident databases held at TRL, including CCIS, the OTS study and the Heavy Vehicle Crash Injury study. This has involved work in a large number of areas, including vehicle compatibility, car occupant thorax injuries, safety priorities for large vehicles, speed-related crashes, and pedestrian accidents. The work on pedestrians has involved using other sources of data, such as the Hospital Episode Statistics (HES), and working with the Helicopter Emergency Medical Service (HEMS) based at the Royal London Hospital. This has led to a number of papers presented at different conferences in Europe. David has also recently begun a part-time PhD, investigating pedestrian impacts with small cars.
Car rollover mechanisms and injury outcome
Richard Cuerden, Rebecca Cookson and David Richards

ABSTRACT: The study focused on the mechanisms which result in passenger cars overturning. Approximately 21% of the car occupant fatalities examined in the UK’s Co-operative Crash Injury Study (CCIS) experienced a rollover. However, rollovers are shown to be complex events, which can occur with or without impact(s) and are not always the principal cause of the resulting occupant injuries.

The study differentiates the different types of rollovers and presents the influencing factors which precede them. Rollover events are divided into three categories: simple rollovers, which do not involve a significant impact; rollovers followed by impact(s); and impacts followed by rollovers.

The research correlated a car’s dynamic motion immediately prior to the initiation of the roll, the mechanisms which cause a car to roll and the consequences with respect to occupant injury. A significant proportion of the cars examined were identified as “sliding” laterally to some degree prior to the roll, and off-road soft surfaces such as grass or earth were the most frequent roll initiators. Cars were also described as skidding or having lost control prior to leaving the road or striking a kerb or other roadside object or other vehicle. For this reason, Electronic Stability Control (ESC) systems were identified as an important countermeasure with respect to potentially preventing a proportion of future rollover accidents.

Occupants who were either fully or partially ejected from their cars were strongly linked to severe injury outcome. Seat belts (ideally used in conjunction with other restraint devices designed to prevent either all or part of the occupants’ body leaving the car through window apertures during the rollover) were shown to be effective.

INTRODUCTION
The data source for this paper is the UK’s Co-operative Crash Injury Study (CCIS), which is one of Europe’s largest car occupant injury causation studies (www.ukccis.org).

The programme of research started in 1983 and continues to investigate real-life car accidents. Multidisciplinary teams examine crashed vehicles and correlate their findings with the injuries the victims suffered in order to determine how car occupants are injured. The objective of the study is to improve car crash performance by continuing to develop a scientific knowledge base, which is used to identify the future priorities for vehicle safety design as changes take place.

CCIS investigates and interprets real-world car occupant injury crashes retrospectively. Police-reported injury road traffic crashes from defined geographical areas of England are reviewed to establish if they meet the CCIS sample criteria. The
RESULTS AND DISCUSSION

The relationship between impact type and injury severity for the car occupants in CCIS is shown in Table 1. In total, of the 8526 occupants recorded in CCIS with known MAIS, 1341 (16%) were in cars which rolled over.

<table>
<thead>
<tr>
<th>Type of collision</th>
<th>Survivors (MAIS)</th>
<th>Killed</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>0</td>
<td>1</td>
<td>2+</td>
</tr>
<tr>
<td>Single impact</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Frontal</td>
<td>642</td>
<td>1840</td>
<td>740</td>
</tr>
<tr>
<td>Right side</td>
<td>204</td>
<td>601</td>
<td>172</td>
</tr>
<tr>
<td>Left side</td>
<td>128</td>
<td>334</td>
<td>142</td>
</tr>
<tr>
<td>Rear</td>
<td>49</td>
<td>204</td>
<td>18</td>
</tr>
<tr>
<td>Multiple impact</td>
<td>256</td>
<td>856</td>
<td>303</td>
</tr>
<tr>
<td>Rollover</td>
<td>176</td>
<td>776</td>
<td>284</td>
</tr>
<tr>
<td>Other</td>
<td>9</td>
<td>7</td>
<td>4</td>
</tr>
<tr>
<td>Total</td>
<td>1464</td>
<td>4618</td>
<td>1663</td>
</tr>
</tbody>
</table>

Rollovers are over-represented for occupants with higher injury severities, especially for occupants who were killed: of the 511 fatally injured occupants, 105 (21%) were in rollovers.

Single-vehicle accidents made up 38% of all accidents which resulted in serious or fatal injury (MAIS 2+) in the CCIS dataset. Rollovers occurred in 7% of multi-vehicle and 41% of single-vehicle accidents. Of all the rollover accidents, 73% were single-vehicle accidents (Figure 1).

CCIS examines cars and car derivatives (light goods/commercial vans). Comparing the proportions of different vehicle types involved in CCIS accidents showed that 31% of off-road vehicles rolled over compared with 9% of estate cars (Figure 2).
Depending on exactly what caused them to roll, the groups where a rollover occurred before an impact are the groups of casualties for whom the rollover might have been prevented if an active safety system, such as Electronic Stability Control (ESC), had been fitted to the vehicle\(^3\). A limitation of this analysis was that the fitment of ESC systems was not correlated with the pre-roll vehicle dynamics. Future work is planned to account for these systems, and to quantify their real-world effects and potential limitations.

The following diagrams (Figure 3 and Figure 4) show how the data were grouped for the analysis from this point on. The occupants were split by severity, with the “non-injured” and “slight” casualties (MAIS 0–1) separated from the “serious and killed” (MAIS 2–6) casualties. Further, two of the casualties shown in Table 2 experienced an “other” type of rollover event and have been excluded from Figure 3 and Figure 4, respectively.

Table 2 categorises the occupants involved in rollovers into four distinct groups, depending on whether there was a significant impact as well as the rollover, and whether that impact occurred before or after the roll. Fay et al.\(^2\) presented similar results and also commented that:

“**In practice, the characteristics of vehicle rollover can be more complicated than such analyses suggest because of the large number of vehicles which experience multiple events in crash sequences, including combinations of impacts and rollover events.**”

Table 2: Categories of rollover

<table>
<thead>
<tr>
<th>Type of rollover</th>
<th>Survivors (MAIS)</th>
<th>Killed</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rolled before first impact</td>
<td>0</td>
<td>15</td>
<td>20</td>
</tr>
<tr>
<td>Rolled after last impact</td>
<td>96</td>
<td>79</td>
<td>31</td>
</tr>
<tr>
<td>Rolled without any impacts*</td>
<td>59</td>
<td>390</td>
<td>149</td>
</tr>
<tr>
<td>Rolled between impacts</td>
<td>6</td>
<td>17</td>
<td>11</td>
</tr>
<tr>
<td>Other</td>
<td>-</td>
<td>-1</td>
<td>1</td>
</tr>
<tr>
<td>Total</td>
<td>176</td>
<td>776</td>
<td>284</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>1341</strong></td>
<td><strong>776</strong></td>
<td><strong>284</strong></td>
</tr>
</tbody>
</table>

* Significant impacts.
Occupants who had a roll then an impact, or a roll but no impact, are subsets of the “Rollover+” group – occupants for whom the rollover occurred first. This was the first group of occupants studied to see which factors influenced or caused their vehicles to roll. The characteristics of the pre-roll events were then compared with the respective injury outcomes. The occupants in the two subsets of rollover that this group encompasses were also analysed. Following this, the occupants in vehicles which had an impact first, then rolled over, were investigated.

Rolled first
This section investigates the characteristics of the rollovers where the rollover occurred before an impact, or where there was no impact. Table 3 shows how the cars’ attempted manoeuvres related to the direction of travel of the cars immediately before the rollover, for the occupants whose car rolled before any impact (or rolled and did not have an impact).

A large number of these vehicles were travelling on left and right bends, and were sliding (they had lost control). These vehicles accounted for 204 (33%) of the occupants in cars which rolled over first. These are occupants for whom it is possible that ESC might have prevented the rollover and resultant injuries, by preventing the initial loss of control. A further 136 (22%) casualties were in cars described as attempting to proceed “Forwards”, but were also known to be sliding or have lost control prior to rolling. The precise reasons for these vehicles having lost control were not always known, but included poor manoeuvres and avoidance actions such as swerving to negotiate obstacles/other vehicles. It is reasonable to assume that a proportion of these incidents could have been prevented if ESC had been fitted to all the cars.

Table 4 shows the initiating factor of the rollovers. The most frequent initiation of the rollovers for all injury severities was grass/earth or some other soft surface.

With the exception of “tarmac/hard surface”, “other vehicle” and “sharp turning or spinning”, the initiating factors all indicate that the vehicle left the carriageway or struck something on the edge of the carriageway.

Table 5 shows the direction of roll of the vehicle, and the seating position and injury severity of the occupants. The majority of the casualties (96%) either rolled right to left or left to right. In order to simplify the analysis of roll direction and seating positions, Occupants who had a roll then an impact, or a roll but no impact, are subsets of the “Rollover+” group – occupants for whom the rollover occurred first. This was the first group of occupants studied to see which factors influenced or caused their vehicles to roll. The characteristics of the pre-roll events were then compared with the respective injury outcomes. The occupants in the two subsets of rollover that this group encompasses were also analysed. Following this, the occupants in vehicles which had an impact first, then rolled over, were investigated.

**Table 3:** Manoeuvre prior to event versus direction of travel at start of event – rolled first

<table>
<thead>
<tr>
<th>Cars’ direction of travel at the start of event</th>
<th>Forwards</th>
<th>Left bend</th>
<th>Right bend</th>
<th>Other / not known</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>Forwards</td>
<td>107</td>
<td>37</td>
<td>31</td>
<td>24</td>
<td>199</td>
</tr>
<tr>
<td>Forwards and sliding to right</td>
<td>67</td>
<td>60</td>
<td>19</td>
<td>9</td>
<td>155</td>
</tr>
<tr>
<td>Forwards and sliding to left</td>
<td>49</td>
<td>8</td>
<td>63</td>
<td>3</td>
<td>123</td>
</tr>
<tr>
<td>Rearwards</td>
<td></td>
<td>4</td>
<td>4</td>
<td>4</td>
<td>4</td>
</tr>
<tr>
<td>Rearwards and sliding to right</td>
<td>2</td>
<td>4</td>
<td>6</td>
<td></td>
<td>12</td>
</tr>
<tr>
<td>Rearwards and sliding to left</td>
<td>3</td>
<td>1</td>
<td>-</td>
<td>-</td>
<td>4</td>
</tr>
<tr>
<td>Purely sideways to right</td>
<td>9</td>
<td>11</td>
<td>12</td>
<td>1</td>
<td>33</td>
</tr>
<tr>
<td>Purely sideways to left</td>
<td>6</td>
<td>3</td>
<td>17</td>
<td>-</td>
<td>26</td>
</tr>
<tr>
<td>Not known</td>
<td>42</td>
<td>1</td>
<td>-</td>
<td>11</td>
<td>54</td>
</tr>
<tr>
<td>Total</td>
<td>285</td>
<td>129</td>
<td>148</td>
<td>48</td>
<td>610</td>
</tr>
</tbody>
</table>

**Table 4:** Roll initiation – rolled first

<table>
<thead>
<tr>
<th>Roll initiation influence</th>
<th>Survivors (MAIS)</th>
<th>Killed</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>0</td>
<td>1</td>
<td>2+</td>
</tr>
<tr>
<td>Kerb</td>
<td>14</td>
<td>62</td>
<td>24</td>
</tr>
<tr>
<td>Gradient up</td>
<td>2</td>
<td>11</td>
<td>12</td>
</tr>
<tr>
<td>Gradient down</td>
<td>8</td>
<td>31</td>
<td>11</td>
</tr>
<tr>
<td>Grass / earth or soft surface</td>
<td>30</td>
<td>158</td>
<td>47</td>
</tr>
<tr>
<td>Tarmac / hard surface</td>
<td>14</td>
<td>67</td>
<td>15</td>
</tr>
<tr>
<td>Other vehicle</td>
<td>1</td>
<td>7</td>
<td>2</td>
</tr>
<tr>
<td>Safety barrier / low structure</td>
<td>-</td>
<td>8</td>
<td>3</td>
</tr>
<tr>
<td>Fence / high structure</td>
<td>-</td>
<td>3</td>
<td>1</td>
</tr>
<tr>
<td>Sharp turning or spinning</td>
<td>3</td>
<td>11</td>
<td>5</td>
</tr>
<tr>
<td>Not known</td>
<td>2</td>
<td>10</td>
<td>3</td>
</tr>
<tr>
<td>Total</td>
<td>74</td>
<td>368</td>
<td>123</td>
</tr>
</tbody>
</table>
position in the car, the offside occupants in cars which rolled
to the right were combined with the nearside occupants in cars
which rolled to the left, and vice versa, to create two groups.
Only seat-belted occupants were selected. The injury severity of
these groups is shown in Table 6.

This shows that occupants seated on the opposite side to the
direction of roll (e.g. drivers whose cars rolled from right to left)
tend to be more severely injured. This may be related to the
kinematics of the occupants at the moment the roof makes
contact with the ground – the occupant seated on the opposite
side to the roll will accelerate towards the roof more than the
occupant seated on the same side to the roll.

### Table 5: Direction of roll by seating position and injury severity – rolled first

<table>
<thead>
<tr>
<th>Direction of roll</th>
<th>Survivors (MAIS)</th>
<th>Killed</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>0</td>
<td>1</td>
<td>2+</td>
</tr>
<tr>
<td>Roll to right</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Driver</td>
<td>21</td>
<td>122</td>
<td>40</td>
</tr>
<tr>
<td>Front passenger</td>
<td>9</td>
<td>46</td>
<td>11</td>
</tr>
<tr>
<td>Rear passenger</td>
<td>9</td>
<td>30</td>
<td>15</td>
</tr>
<tr>
<td>Not known</td>
<td>-</td>
<td>1</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td>39</td>
<td>199</td>
<td>66</td>
</tr>
<tr>
<td>Roll to left</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Driver</td>
<td>10</td>
<td>89</td>
<td>39</td>
</tr>
<tr>
<td>Front passenger</td>
<td>8</td>
<td>40</td>
<td>8</td>
</tr>
<tr>
<td>Rear passenger</td>
<td>14</td>
<td>26</td>
<td>3</td>
</tr>
<tr>
<td>Not known</td>
<td>1</td>
<td>1</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td>33</td>
<td>156</td>
<td>50</td>
</tr>
<tr>
<td>Rear over front</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Driver</td>
<td>-</td>
<td>7</td>
<td>4</td>
</tr>
<tr>
<td>Front passenger</td>
<td>1</td>
<td>2</td>
<td>1</td>
</tr>
<tr>
<td>Rear passenger</td>
<td>-</td>
<td>2</td>
<td>-</td>
</tr>
<tr>
<td>Not known</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td>1</td>
<td>11</td>
<td>5</td>
</tr>
<tr>
<td>Front over rear</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Driver</td>
<td>1</td>
<td>1</td>
<td>-</td>
</tr>
<tr>
<td>Front passenger</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Rear passenger</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Not known</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td>1</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>Not known</td>
<td>0</td>
<td>1</td>
<td>2</td>
</tr>
<tr>
<td>Total</td>
<td>74</td>
<td>368</td>
<td>123</td>
</tr>
</tbody>
</table>

### Table 6: Roll direction and seating position – rolled first

<table>
<thead>
<tr>
<th>Roll direction and seating position</th>
<th>MAIS 0–1</th>
<th>MAIS 2–6</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>Seated on side adjacent to direction of roll</td>
<td>133 (78.7%)</td>
<td>36 (21.3%)</td>
<td>169</td>
</tr>
<tr>
<td>Seated on opposite side to direction of roll</td>
<td>115 (72.3%)</td>
<td>44 (27.7%)</td>
<td>159</td>
</tr>
<tr>
<td>Total</td>
<td>248</td>
<td>80</td>
<td>328</td>
</tr>
</tbody>
</table>
Figure 7 shows the surface on which the vehicles that rolled over landed. There is virtually no correlation between the landing surface and the direction of roll, implying that cars leave the carriageway to the left and right evenly.

Roll and no impact

The “roll and no impact” group is a subsection of the “rolled first” group. This section analyses the characteristics and consequences of rolls where there was no impact.

Figure 8 shows the relationship between the number of rolls and the injury severity of the occupants. The number of rolls is recorded as multiples of 0.25, where 0.25 rolls would be a roll onto the side, 0.5 rolls would be a roll onto the roof, etc.
Occupants in vehicles which rolled two or more times tend to be more severely injured, although there were relatively few vehicles that rolled this often. Slightly injured occupants are over-represented in vehicles which rolled 0.5 times.

Figure 9 shows the relationship between injury severity of the occupants, and whether their vehicle was airborne during the rollover.

![Figure 9: Severity of occupants and whether vehicle was airborne – roll and no impact](image)

The relationship between injury severity and whether the vehicle was airborne is clearer than the relationship between injury severity and the number of rolls. Of the occupants with MAIS 0–1, the vehicle was not airborne for almost 70% of the occupants. For occupants with MAIS 2–6, the vehicle was not airborne for 55% of the occupants.

For the vehicles which rolled, the most frequent area of most significant damage was the roof (47% in total, 47% of MAIS 0–1 occupants, and 45% of MAIS 2–6 occupants). Table 7 explores the relationship between ejection and seat belt use for the occupants in a vehicle which rolled but had no other impact.

It is clear that seat belt use and full ejection in rollovers are strongly related. Some 65% of occupants who were not ejected were wearing a seat belt, compared with only 10% of occupants who were fully ejected. Occupants who were fully ejected were also much more likely to have severe injuries; 18% of occupants who were not ejected had MAIS 2–6, compared with 90% of the occupants who were fully ejected.

Severe injury was also common among occupants who were partially ejected, with 89% having MAIS 2–6. However, the seat belt use of these occupants was relatively high at 83%, which implies that seat belts prevent full ejection, but other systems (e.g. curtain airbags) are also required in order to prevent partial ejection.

Table 8 and Table 9 show the AIS 2+ and AIS 3+ injuries received by the occupants in cars which rolled over with no other impact.

<table>
<thead>
<tr>
<th>Ejection</th>
<th>Seat belt use</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Used</td>
</tr>
<tr>
<td>None</td>
<td></td>
</tr>
<tr>
<td>MAIS 0–1</td>
<td>231</td>
</tr>
<tr>
<td>MAIS 2–6</td>
<td>42</td>
</tr>
<tr>
<td></td>
<td>273</td>
</tr>
<tr>
<td>Full</td>
<td></td>
</tr>
<tr>
<td>MAIS 0–1</td>
<td>1</td>
</tr>
<tr>
<td>MAIS 2–6</td>
<td>1</td>
</tr>
<tr>
<td></td>
<td>2</td>
</tr>
<tr>
<td>Partial</td>
<td></td>
</tr>
<tr>
<td>MAIS 0–1</td>
<td>3</td>
</tr>
<tr>
<td>MAIS 2–6</td>
<td>17</td>
</tr>
<tr>
<td></td>
<td>20</td>
</tr>
<tr>
<td>Total</td>
<td></td>
</tr>
<tr>
<td>MAIS 0–1</td>
<td>235</td>
</tr>
<tr>
<td>MAIS 2–6</td>
<td>60</td>
</tr>
<tr>
<td></td>
<td>295</td>
</tr>
</tbody>
</table>

Table 8: Proportion of occupants with AIS 2+ injuries, by seat belt use and body region – roll and no impact

<table>
<thead>
<tr>
<th>Injured ISS body region (percentage AIS 2+)</th>
<th>Seat belt use</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Seat belt used</td>
</tr>
<tr>
<td>MAIS 2+ (n)</td>
<td>60</td>
</tr>
<tr>
<td>Head AIS 2+</td>
<td>45%</td>
</tr>
<tr>
<td>Face AIS 2+</td>
<td>1.7%</td>
</tr>
<tr>
<td>Thorax AIS 2+</td>
<td>25%</td>
</tr>
<tr>
<td>Abdomen AIS 2+</td>
<td>13.3%</td>
</tr>
<tr>
<td>Limbs AIS 2+</td>
<td>51.7%</td>
</tr>
<tr>
<td>External AIS 2+</td>
<td>8.3%</td>
</tr>
</tbody>
</table>

Table 9: Proportion of occupants with AIS 3+ injuries, by seat belt use and body region – roll and no impact

<table>
<thead>
<tr>
<th>Injured ISS body region (percentage AIS 3+)</th>
<th>Seat belt use</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Seat belt used</td>
</tr>
<tr>
<td>MAIS 3+ (n)</td>
<td>60</td>
</tr>
<tr>
<td>Head AIS 3+</td>
<td>23.3%</td>
</tr>
<tr>
<td>Face AIS 3+</td>
<td>-</td>
</tr>
<tr>
<td>Thorax AIS 3+</td>
<td>15%</td>
</tr>
<tr>
<td>Abdomen AIS 3+</td>
<td>5%</td>
</tr>
<tr>
<td>Limbs AIS 3+</td>
<td>15%</td>
</tr>
<tr>
<td>External AIS 3+</td>
<td>1.7%</td>
</tr>
</tbody>
</table>
For seat belted occupants, the most frequent AIS 2+ and AIS 3+ injuries were to the head and the limbs. For non-belted occupants, the most frequent AIS 2+ injuries were to the head, thorax and limbs; and the most frequent AIS 3+ injuries were to the head and thorax. Occupants not wearing a seat belt generally had more injuries to more body regions, and the proportion of thorax injuries especially increased for occupants not wearing a seat belt.

Table 10 shows how the injury severity of front seat occupants depended on the direction of the roll. Only occupants wearing a seat belt were selected for this table.

**Table 10**: Roll direction and seating position – roll and no impact

<table>
<thead>
<tr>
<th>Roll direction and seating position</th>
<th>MAIS 0 &amp; 1</th>
<th>MAIS 2–6</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>Seated on side adjacent to direction of roll</td>
<td>105 (80.8%)</td>
<td>25 (19.2%)</td>
<td>130</td>
</tr>
<tr>
<td>Seated on opposite side to direction of roll</td>
<td>83 (72.8%)</td>
<td>31 (27.2%)</td>
<td>114</td>
</tr>
<tr>
<td>Total</td>
<td>188</td>
<td>56</td>
<td>244</td>
</tr>
</tbody>
</table>

This shows that occupants seated on the opposite side to the direction of roll (for example, drivers whose cars rolled from right to left) tend to be more severely injured.

For seat belted occupants only, no statistical relationship was found with respect to the number of rolls, surface rolled onto, initiation influence or initiation type when comparing MAIS 0-1 and MAIS 2-6 occupants. However, the proportion of occupants in airborne vehicles was greater for MAIS 2-6.

**Roll followed by impact**

The group of occupants whose vehicle rolled before having an impact is also a subset of the occupants who rolled first. However, this group of 145 occupants is relatively small compared with the number who rolled over without an impact, so less detail is presented. Also, because these vehicles had an impact following the rollover it is difficult to distinguish the injurious effects of the rollover from those of the impact.

Figure 10 shows the relationship between the number of rolls of the vehicle and the injury severity of the occupants. This shows no clear relationship between the two variables, but the vehicles that rolled with impact, as expected, rolled fewer times than those which rolled without subsequent impact(s).

Figure 11 compares the injury severity of the occupants with whether their vehicle was airborne.

As for rollovers with no impact, the severity is greater in rollovers where the vehicle has become airborne.
Table 11: Ejection and seat belt use – roll followed by impact

<table>
<thead>
<tr>
<th>Ejection</th>
<th>Seat belt use</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Used</td>
<td>Not used</td>
</tr>
<tr>
<td>None</td>
<td></td>
<td></td>
</tr>
<tr>
<td>MAIS 0–1</td>
<td>71</td>
<td>5</td>
</tr>
<tr>
<td>MAIS 2–6</td>
<td>22</td>
<td>6</td>
</tr>
<tr>
<td>Full</td>
<td></td>
<td></td>
</tr>
<tr>
<td>MAIS 0–1</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>MAIS 2–6</td>
<td>5</td>
<td>3</td>
</tr>
<tr>
<td>Partial</td>
<td></td>
<td></td>
</tr>
<tr>
<td>MAIS 0–1</td>
<td>1</td>
<td>-</td>
</tr>
<tr>
<td>MAIS 2–6</td>
<td>6</td>
<td>3</td>
</tr>
<tr>
<td>Total</td>
<td>99</td>
<td>23</td>
</tr>
</tbody>
</table>

All of the occupants who were fully ejected, and for whom seat belt use was known, were not wearing a seat belt. These occupants were all seriously injured or killed.

Table 12 and Table 13 show the proportion of AIS 2+ and AIS 3+ injuries received by the occupants by body region and seat belt use.

Table 12: Proportion of occupants with AIS 2+ injuries, by seat belt use and body region – roll followed by impact

<table>
<thead>
<tr>
<th>Injured ISS body region (percentage AIS 2+)</th>
<th>Seat belt used</th>
<th>Seat belt not used</th>
<th>Seat belt use not known</th>
</tr>
</thead>
<tbody>
<tr>
<td>MAIS 2+ (n)</td>
<td>27</td>
<td>18</td>
<td>6</td>
</tr>
<tr>
<td>Head AIS 2+</td>
<td>52%</td>
<td>72%</td>
<td>50%</td>
</tr>
<tr>
<td>Face AIS 2+</td>
<td>11%</td>
<td>6%</td>
<td>-</td>
</tr>
<tr>
<td>Thorax AIS 2+</td>
<td>59%</td>
<td>72%</td>
<td>67%</td>
</tr>
<tr>
<td>Abdomen AIS 2+</td>
<td>19%</td>
<td>33%</td>
<td>17%</td>
</tr>
<tr>
<td>Limbs AIS 2+</td>
<td>56%</td>
<td>50%</td>
<td>50%</td>
</tr>
<tr>
<td>External AIS 2+</td>
<td>4%</td>
<td>-</td>
<td>17%</td>
</tr>
</tbody>
</table>

Similarly to rollovers without impacts, the injuries were dominated by head, thorax and limb injuries. Occupants who were not wearing a seat belt had more injuries to more body regions, especially head and thorax injuries.

Table 13: Proportion of occupants with AIS 3+ injuries, by seat belt use and body region – roll followed by impact

<table>
<thead>
<tr>
<th>Injured ISS body region (percentage AIS 3+)</th>
<th>Seat belt used</th>
<th>Seat belt not used</th>
<th>Seat belt use not known</th>
</tr>
</thead>
<tbody>
<tr>
<td>MAIS 3+ (n)</td>
<td>27</td>
<td>18</td>
<td>6</td>
</tr>
<tr>
<td>Head AIS 3+</td>
<td>48%</td>
<td>61%</td>
<td>50%</td>
</tr>
<tr>
<td>Face AIS 3+</td>
<td>-</td>
<td>6%</td>
<td>-</td>
</tr>
<tr>
<td>Thorax AIS 3+</td>
<td>44%</td>
<td>61%</td>
<td>67%</td>
</tr>
<tr>
<td>Abdomen AIS 3+</td>
<td>4%</td>
<td>28%</td>
<td>-</td>
</tr>
<tr>
<td>Limbs AIS 3+</td>
<td>15%</td>
<td>17%</td>
<td>-</td>
</tr>
<tr>
<td>External AIS 3+</td>
<td>-</td>
<td>6%</td>
<td>33%</td>
</tr>
</tbody>
</table>

Impact followed by roll

Rollovers which occur after an impact are likely to be different to rollovers which occur before an impact or with no impact. Because this paper concentrates on the causes and consequences of rollovers, factors which are likely to be affected by the initial impact as well as the rollover – and where the effects of each cannot be distinguished (e.g. roll direction and injury severity by seating position) – have not been analysed here.

Table 14 shows the relationship between the manoeuvre prior to the impact and the car’s direction of travel at the start of the event. Compared with rollovers which occurred before/without an impact, a smaller proportion were sliding and travelling around a bend (16% compared with 33%). This suggests that the prevention of loss of control by ESC would have had a relatively smaller effect in reducing rollover for these occupants. Similarly, the casualties described as occurring in cars travelling “Forwards” and sliding laterally to some degree represent about 28% of the “Impact followed by roll” group. These crashes often involved the car striking another vehicle or object and losing control or spinning before rolling over. ESC is likely to offer fewer benefits in these situations compared with those it can offer the rolled first group.

Table 15 shows the initiating factor of the rollovers by the injury severity of the occupants. Compared with rollovers which occurred before/without an impact, the proportion of rollovers involving another vehicle was much greater. However, grass/earth or soft surface was still the most frequent initiating factor.

Figure 12 and Figure 13 show the direction of the initiation force and the point of action of this force respectively.

The majority of rolls to the right and left are still caused by initiation forces to the left and right wheels, respectively.
Table 14: Manoeuvre prior to event versus direction of travel at start of event – impact followed by roll

<table>
<thead>
<tr>
<th>Cars' direction of travel at the start of event</th>
<th>Manoeuvre prior to event</th>
<th>Other / not known</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Forwards</td>
<td>Left bend</td>
<td>Right bend</td>
</tr>
<tr>
<td>Forwards</td>
<td>178</td>
<td>46</td>
<td>27</td>
</tr>
<tr>
<td>Forwards and sliding to right</td>
<td>74</td>
<td>15</td>
<td>11</td>
</tr>
<tr>
<td>Forwards and sliding to left</td>
<td>58</td>
<td>11</td>
<td>30</td>
</tr>
<tr>
<td>Rearwards</td>
<td>4</td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td>Rearwards and sliding to right</td>
<td>5</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Rearwards and sliding to left</td>
<td>2</td>
<td>9</td>
<td>-</td>
</tr>
<tr>
<td>Purely sideways to right</td>
<td>39</td>
<td>16</td>
<td>3</td>
</tr>
<tr>
<td>Purely sideways to left</td>
<td>19</td>
<td>5</td>
<td>19</td>
</tr>
<tr>
<td>Not known</td>
<td>42</td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td>Total</td>
<td>421</td>
<td>106</td>
<td>94</td>
</tr>
</tbody>
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Table 15: Roll initiation – impact followed by roll

<table>
<thead>
<tr>
<th>Roll initiation influence</th>
<th>Survivors (MAIS)</th>
<th>Killed</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>0</td>
<td>1</td>
<td>2+</td>
</tr>
<tr>
<td>Kerb</td>
<td>10</td>
<td>43</td>
<td>12</td>
</tr>
<tr>
<td>Gradient up</td>
<td>2</td>
<td>15</td>
<td>6</td>
</tr>
<tr>
<td>Gradient down</td>
<td>8</td>
<td>30</td>
<td>16</td>
</tr>
<tr>
<td>Grass / earth or soft surface</td>
<td>24</td>
<td>86</td>
<td>33</td>
</tr>
<tr>
<td>Tarmac / hard surface</td>
<td>13</td>
<td>78</td>
<td>15</td>
</tr>
<tr>
<td>Other vehicle</td>
<td>14</td>
<td>62</td>
<td>15</td>
</tr>
<tr>
<td>Safety barrier / low structure</td>
<td>12</td>
<td>43</td>
<td>28</td>
</tr>
<tr>
<td>Fence / high structure</td>
<td>5</td>
<td>19</td>
<td>18</td>
</tr>
<tr>
<td>Sharp turning or spinning</td>
<td>9</td>
<td>14</td>
<td>11</td>
</tr>
<tr>
<td>Other</td>
<td>-</td>
<td>6</td>
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<tr>
<td>Not known</td>
<td>5</td>
<td>11</td>
<td>6</td>
</tr>
<tr>
<td>Total</td>
<td>102</td>
<td>407</td>
<td>160</td>
</tr>
</tbody>
</table>

Figure 12: Direction of roll initiation force – impact followed by roll

Figure 13: Point of action of initiation force – impact followed by roll
Figure 14 shows that the surface the vehicles landed on was not related to the direction of the roll, but that a landing on the carriageway or road surface was proportionally much more common (~45%) compared with roll first incidents (~30%).

Figure 15 shows the relationship between the number of rolls and the MAIS of the occupants.

Figure 16: Severity of occupants and whether vehicle was airborne – impact followed by a roll

This figure shows that just over 60% of the MAIS 2–6 occupants were in a vehicle which did not become airborne, compared with about 80% of MAIS 0–1 occupants.

Table 16 explores the relationship between seat belt use, ejection and injury severity.

Table 16: Ejection and seat belt use – impact followed by roll

<table>
<thead>
<tr>
<th>Ejection</th>
<th>Seat belt use</th>
<th></th>
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<tr>
<td></td>
<td>Used</td>
<td>Not used</td>
<td>Not known</td>
<td></td>
</tr>
<tr>
<td>None</td>
<td>MAIS 0–1</td>
<td>310</td>
<td>61</td>
<td>124</td>
</tr>
<tr>
<td></td>
<td>MAIS 2–6</td>
<td>100</td>
<td>36</td>
<td>31</td>
</tr>
<tr>
<td></td>
<td></td>
<td>410</td>
<td>97</td>
<td>155</td>
</tr>
<tr>
<td>Full</td>
<td>MAIS 0–1</td>
<td>-</td>
<td>4</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td>MAIS 2–6</td>
<td>4</td>
<td>20</td>
<td>2</td>
</tr>
<tr>
<td></td>
<td></td>
<td>4</td>
<td>24</td>
<td>2</td>
</tr>
<tr>
<td>Partial</td>
<td>MAIS 0–1</td>
<td>5</td>
<td>2</td>
<td>3</td>
</tr>
<tr>
<td></td>
<td>MAIS 2–6</td>
<td>10</td>
<td>9</td>
<td>6</td>
</tr>
<tr>
<td></td>
<td></td>
<td>15</td>
<td>11</td>
<td>9</td>
</tr>
<tr>
<td>Not known</td>
<td>MAIS 0–1</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td>MAIS 2–6</td>
<td>-</td>
<td>2</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td></td>
<td>-</td>
<td>2</td>
<td>-</td>
</tr>
<tr>
<td>Total</td>
<td>MAIS 0–1</td>
<td>315</td>
<td>67</td>
<td>127</td>
</tr>
<tr>
<td></td>
<td>MAIS 2–6</td>
<td>114</td>
<td>67</td>
<td>39</td>
</tr>
<tr>
<td></td>
<td></td>
<td>429</td>
<td>134</td>
<td>166</td>
</tr>
</tbody>
</table>

Occupants in a vehicle which rolled 0.25 times and 0.5 times tended to have a lower injury severity compared with those occupants in vehicles with more rolls. However, there is a much clearer relationship between injury severity and whether the vehicle became airborne, which is shown in Figure 16.
CONCLUSIONS
Approximately 21% of the car occupant fatalities examined in the UK’s CCIS experienced a rollover. However, rollovers are shown to be complex events, which can occur with or without impact(s) and which are not always the principal cause of the resulting occupant injuries.

The study differentiates the different types of rollovers for MAIS 2+ occupants:

- Rollovers which do not involve a significant impact (30.1%)
- Rollovers followed by impact(s) (13.1%)
- Impacts followed by rollovers (56.5%)

For cars which rolled first, 33% were described as travelling on bends (turning) and “sliding” laterally, and 22% were described as originally intending to proceed “Forwards” but had also “lost control”. ESC was identified as an important countermeasure with respect to potentially preventing a proportion of these rollover accidents. For cars which had an impact before rollover, the potential effectiveness of ESC is likely to be less.

The most common roll initiation influence was off-road soft ground (grass or earth) applying force to both wheels (right or left).

Casualties in cars which became airborne during the roll suffered proportionally more serious injuries.

Occupants who were either fully or partially ejected from their cars were strongly linked to severe injury outcome. Seat belts (ideally used in conjunction with other restraint devices designed to prevent either all or part of the occupants’ body leaving the car through window apertures during the rollover) were shown to be effective.

ACKNOWLEDGEMENTS
This paper uses accident data from the United Kingdom’s Cooperative Crash Injury Study (CCIS) collected during the period 2002–2008 (Phases 7s and 8h). Currently, CCIS is managed by the Transport Research Laboratory (TRL Limited), on behalf of the United Kingdom’s Department for Transport (DfT) (Transport Technology and Standards Division), who fund the project along with Autoliv, Fiat, Ford Motor Company, Nissan Motor Company and Toyota Motor Europe. Previous sponsors include Daimler Chrysler, LAB, Rover Group Limited, Visteon, Volvo Car Corporation, Daewoo Motor Company Limited and Honda R&D Europe (UK) Limited. Data were collected by teams from the Birmingham Automotive Safety Centre of the University of Birmingham, the Vehicle Safety Research Centre at Loughborough University, TRL Limited and the Vehicle & Operator Services Agency (VOSA) of DfT.

Further information on CCIS can be found at www.ukccis.org

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REFERENCES


SUMMARY TABLES

Table A 1: Severity of injuries related to seating position and sex

<table>
<thead>
<tr>
<th>Seating position + sex</th>
<th>Survivors (MAIS)</th>
<th>Killed</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>Driver</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Male</td>
<td>64</td>
<td>297</td>
<td>142</td>
</tr>
<tr>
<td>Female</td>
<td>27</td>
<td>174</td>
<td>48</td>
</tr>
<tr>
<td>Not known</td>
<td>1</td>
<td>2</td>
<td>3</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>92</strong></td>
<td><strong>473</strong></td>
<td><strong>190</strong></td>
</tr>
<tr>
<td>Front passenger</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Male</td>
<td>20</td>
<td>89</td>
<td>27</td>
</tr>
<tr>
<td>Female</td>
<td>16</td>
<td>84</td>
<td>31</td>
</tr>
<tr>
<td>Not known</td>
<td>6</td>
<td></td>
<td>6</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>42</strong></td>
<td><strong>173</strong></td>
<td><strong>58</strong></td>
</tr>
<tr>
<td>Rear passenger</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Male</td>
<td>21</td>
<td>60</td>
<td>18</td>
</tr>
<tr>
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<td>65</td>
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<tr>
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<td>2</td>
<td>6</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>38</strong></td>
<td><strong>127</strong></td>
<td><strong>36</strong></td>
</tr>
<tr>
<td>Total</td>
<td>176</td>
<td>776</td>
<td>284</td>
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Table A 2: Severity of injuries related to seating position and belt use

<table>
<thead>
<tr>
<th>Seating position + belt</th>
<th>Survivors (MAIS)</th>
<th>Killed</th>
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</thead>
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<tr>
<td>Driver</td>
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</tr>
<tr>
<td>Belted</td>
<td>53</td>
<td>359</td>
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<tr>
<td>Unbelted</td>
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<td>34</td>
<td>44</td>
</tr>
<tr>
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<td>80</td>
<td>36</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>92</strong></td>
<td><strong>473</strong></td>
<td><strong>190</strong></td>
</tr>
<tr>
<td>Front passenger</td>
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<td></td>
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</tr>
<tr>
<td>Belted</td>
<td>30</td>
<td>109</td>
<td>37</td>
</tr>
<tr>
<td>Unbelted</td>
<td>2</td>
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</tr>
<tr>
<td>Not known</td>
<td>10</td>
<td>46</td>
<td>8</td>
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<td><strong>Total</strong></td>
<td><strong>42</strong></td>
<td><strong>173</strong></td>
<td><strong>58</strong></td>
</tr>
<tr>
<td>Rear passenger</td>
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</tr>
<tr>
<td>Belted</td>
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</tr>
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<td>Unbelted</td>
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<td><strong>127</strong></td>
<td><strong>36</strong></td>
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<tr>
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<td><strong>Total</strong></td>
<td><strong>176</strong></td>
<td><strong>776</strong></td>
<td><strong>284</strong></td>
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Table A 3: Severity of injuries related to seating position and age

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<td>&lt;17</td>
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</tr>
<tr>
<td>17–24</td>
<td>28</td>
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<td>63</td>
</tr>
<tr>
<td>25–39</td>
<td>21</td>
<td>156</td>
<td>66</td>
</tr>
<tr>
<td>40–59</td>
<td>21</td>
<td>87</td>
<td>39</td>
</tr>
<tr>
<td>60+</td>
<td>12</td>
<td>37</td>
<td>20</td>
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<td>Not known</td>
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<td>20</td>
<td>2</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>92</strong></td>
<td><strong>473</strong></td>
<td><strong>190</strong></td>
</tr>
<tr>
<td>Front passenger</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>&lt;17</td>
<td>4</td>
<td>18</td>
<td>4</td>
</tr>
<tr>
<td>17–24</td>
<td>5</td>
<td>73</td>
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<td>25–39</td>
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<td>40–59</td>
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<td><strong>Total</strong></td>
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<td><strong>173</strong></td>
<td><strong>58</strong></td>
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<tr>
<td>Rear passenger</td>
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</tr>
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<td>&lt;17</td>
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<td>4</td>
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</tr>
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<td><strong>Total</strong></td>
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<td><strong>127</strong></td>
<td><strong>36</strong></td>
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<tr>
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<td><strong>Total</strong></td>
<td><strong>176</strong></td>
<td><strong>776</strong></td>
<td><strong>284</strong></td>
</tr>
</tbody>
</table>

Total 176 776 284 105 1341
This paper details the outcomes of research commissioned by Transport for London (TfL), and was presented at the Young Researchers Seminar in Turin, Italy, 3–5 June 2009, which was organised by the European Conference of Transport Research Institutes (ECTRI), Forum of European National Highway Research Laboratories (FEHRL) and Forum of European Road Safety Institutes (FERSI). It is based on an earlier paper published by Planning and Transport, Research and Computation (PTRC) in the Proceedings of the Traffic Management Conference, 23–25 March 2009, with contributing authors Helen Gibson, David Bretherton, Gareth Bowen and Adam Giszczak from TRL, and Chris D’Souza from TfL.

Dr Helen Gibson joined TRL three years ago, after completing a PhD in Computational Physics. Since then, she has become involved in several areas of transport including the Strategic Transport Model (STM), the roundabout model ARCADY, developing a spreadsheet based on COst–Benefit Assessment (COBA) equations to calculate benefits of an Area Travel Plan, designing a Car Availability Model for Dubai, and studying new cancel detection logic in the Split, Cycle and Offset Optimisation Technique (SCOOT) system, which is the topic of the following paper. Since carrying out the study described in the paper, she has also become involved in SCOOT Maintenance, and research into calculating the benefits of coordination versus the benefits of running a node at its minimum practical cycle time. It is anticipated that this work will lead to further improvements in the efficiency of the SCOOT system, by providing an automatic trigger to remove nodes from regions when the benefits of coordination have been lost.
ABSTRACT: SCOOT (Split, Cycle and Offset Optimisation Technique) is an adaptive traffic signal control system. Taking information from strategically placed detectors, it optimises the signal timings over a network on a second-by-second basis.

Transport for London (TfL) has a policy of providing priority to buses at intersections, and is now making use of iBus, a GPS-based system which can provide bus detection in a way that is much less expensive than beacons or conventional in-road loop detectors.

In response, SCOOT’s bus priority logic has been updated. Previously, if there was a bus stop near a junction the detector had to be placed after the bus stop, giving SCOOT only a few seconds to respond. The new logic allows longer journey times to be acted on, permitting the detection to be placed before the bus stop. With the introduction of pre-pay fares, bus-stop dwell times (the period that a bus is stationary at a stop) have become more consistent, and the uncertainty in the journey time has been reduced. However, to offset the uncertainty further, cancel-detection logic has also been introduced, which informs SCOOT when the bus has gone through and allows it to cut short the traffic signal’s “green extension” if possible.

This paper presents the result of traffic modelling simulations using a microsimulation traffic model, VISSIM\(^1\), and the new SCOOT logic. Results are presented from various scenarios, with and without bus priority, utilising downstream or upstream bus detection, and with and without the use of a cancel detector. The effect of various SCOOT parameters, including the uncertainty in bus journey time, is demonstrated. The optimum location of the cancel detector, given the transmission lags involved, is also presented.

1 VISSIM is a German acronym, “Verkehr In Städten – SIMulationsmodell”. It is a model for simulating traffic in cities and was developed by the German company PTV (Planung Transport Verkehr).

1 INTRODUCTION

In this paper, the evaluation of new bus priority logic in SCOOT, a traffic signal control system, is presented. The most effective way that priority is granted to a bus is by extending the green signal until the vehicle gets through. Using the original bus priority logic, bus detection would be sited 15 seconds from the stop line. However, if there was a bus stop near the stop line the detection would have to occur after the bus had left the stop, often only leaving a few seconds for SCOOT to react.

In London, iBus, a GPS-based system, is used for tracking buses. This means that it is possible to install “virtual” bus detectors that are much cheaper than traditional detectors. In addition, the time that a bus stays at a bus stop has become more consistent with the introduction of flat fares, pre-pay systems and three-door articulated buses.

Therefore, the bus priority logic has been updated to make use of multiple detectors and longer bus journey times.
The hypothesis is that detecting the bus earlier allows more extensions to occur, providing the buses with greater savings. However, it is expected that the journey time will be more variable as a result. To compensate for this, extra time is added to the journey duration to make sure the bus gets through. However, if the bus gets through earlier, some of the green extension is “wasted”. Positioning a cancel detector to inform SCOOT that the bus has passed the stop line will avoid this unnecessary green time.

This paper presents the results of a study to determine the best location of a cancel detector. There are transmission lags of five seconds between the street and the central computer. Therefore, it is expected that the optimum location for the cancel detector is some way back from the stop line.

Having determined where the cancel detector should be located, simulations with differing flow conditions and differing SCOOT settings were performed, and some of the results are presented and discussed here.

2 EXISTING SCOOT PRIORITY FACILITIES

SCOOT (Split, Cycle and Offset Optimisation Technique) is an adaptive Urban Traffic Control (UTC) system (www.scoot-utc.com). Taking information from strategically placed detectors, it optimises the signal timings over a network on a second-by-second basis. It is currently operating in over 200 cities worldwide. Since 1996, Version 3.1, SCOOT has included bus priority facilities. Bus priority can be provided through extensions (extending the duration of the green phase long enough to allow the bus through) or recalls (shortening preceding stages).

SCOOT has a number of facilities that can be used to provide priority to buses. “Passive” priority, which does not differen
tiate between vehicles, can be given to links or routes using split and offset weightings. As all vehicles on the weighted link receive a similar benefit, the level of priority that can be given is limited. “Active” priority can be given to individual buses: extensions to prevent a bus being stopped at the start of red, and recalls to start the bus green earlier than normal. In addition, in some situations intermediate stages between the current stage and the bus stage can be skipped. These terms are described more fully in Section 2.3.

Active priority requires that SCOOT be informed of a bus’s presence either by selective vehicle detectors, i.e. using bus loops and transponders on buses, or by an Automatic Vehicle Location (AVL) system. Bus management and information systems such as iBus, which make use of GPS technology to track buses through the network, can also be used to provide bus priority in SCOOT. Bus management systems can additionally provide information on a bus’s adherence to schedule, which provides the option of giving different levels of priority to buses according to how late they are. Differential priority is particularly useful in improving the regularity of high-frequency bus services that run on a “headway” principle.

All these techniques are controlled by user-set parameters to prevent the priority causing undesired extra delay to other vehicles. These different techniques are described in more detail in the following sections.

2.1 Location of bus detection

The best location for detection will usually be a compromise between the need for detection as far upstream as possible and the need for accurate journey time prediction. Prior to recent developments (see “Cancel detection” and “Long journey time” sections below), bus detectors needed to be located downstream of any bus stop, as SCOOT does not attempt to model the time spent at bus stops. Depending on site conditions, a location giving a bus journey time of ten to 15 seconds to the stop line is recommended.

2.2 Modelling

Buses are modelled by SCOOT as queuing with other vehicles. This allows buses to be given priority even though other vehicles may delay them. The effect of bus lanes can also be modelled, including those which end before the stop line.

2.3 Priority

The signal timings are optimised to benefit the buses, by extending a current green signal (an extension), by causing succeeding stages to occur early (a recall) or by “stage skipping”. Extensions can be awarded centrally, or the signal controller can be programmed to implement them locally on street (a local extension). Recalls are always central.

For example, for the three-stage junction illustrated in Figure 1, if a bus is detected towards the end of Stage 1 it will receive an extension as shown in Figure 2. If the bus is detected during a red period, it will receive a recall (i.e. Stage 2 and Stage 3 are shortened, so that Stage 1 starts earlier) as shown in Figure 3. It may also benefit from stage skipping, when Stage 3 is one that may be skipped. Figure 4 shows the result, where Stage 2 has been shortened and Stage 3 completely omitted from this cycle.

2.4 Local extensions

Extensions awarded by the controller can be advantageous, as they eliminate three to five seconds of transmission delay between outstation and instation. (Currently in the London UTC system the transmission lag is five seconds.) That allows the system to grant extensions to buses that arrive in the last few seconds of green. The feature is especially important where link lengths are short, or where bus stops are located near to the stop line. SCOOT is still in control, as it updates each second in order to permit local extensions only when the saturation of the junction is sufficiently low. Techniques for programming the signal controller have been developed and implemented in London.

1 Headway means the time between buses. High-frequency buses are often indicated to arrive “every five minutes” rather than at specific time-tabled times. They are therefore judged on whether there is five minutes between each bus rather than whether the bus arrives at a given time.
Selected papers: Quantifying the benefits of new bus priority logic in SCOOT

Given green. No adverse effects were observed in the trials in London, where great care was taken with the implementation. It is recommended that the principles used in the trials should be adhered to:

- Main road stages should not be skipped
- Pedestrian stages should not be skipped – a possible exception is where the pedestrian phase being skipped occurs more than once per cycle

When stage skipping is to be introduced at a junction, the stage order should be reviewed as it may be desirable to re-order the normal stage sequence. This is especially likely at junctions where it is not permitted to skip a particular stage.
2.7 Restrictions on priority

One of the main advantages of providing priority through SCOOT is that the extent of priority given to buses can be controlled. Extensions and recalls can be restricted depending on the saturation of the junction as modelled by SCOOT. This is managed by specifying target degrees of saturation for both extensions and recalls. The recall target saturation is normally set so that the junction does not become oversaturated. Non-priority stages will be run to the target saturation value. In the case of extensions, the target saturation may be set so that some oversaturation is allowed. An extension will not be granted if to do so would result in the degree of saturation of a link at the node exceeding the target value. This means that bus priority will be most effective at junctions that have spare capacity. Stage skipping has extra controls to limit the frequency of skips in addition to those that prevent skipping of a stage whose degree of saturation is over a user-set level.

2.8 Differential priority

The introduction of real-time passenger information systems such as AVL allows a bus’s location to be compared against a schedule, and in this way priority can be differentiated by a bus’s adherence to schedule.

“Differential priority” refers to the strategy of providing priority on the basis of criteria other than vehicle class alone, such as adherence to schedule. If a “degree of lateness factor” can be determined and provided to SCOOT, SCOOT is then able to provide different levels of priority according to how late a bus is. It can also be used to provide different levels of priority to buses on different routes. The advantages of this approach are that:

- By providing priority to late buses only – and, hence, to fewer buses – a higher level of priority may be given and the disbenefit to other traffic reduced
- Greater improvement in the regularisation of the service will result – and, hence, the waiting time of passengers will be reduced

In SCOOT, it is possible to specify different priority levels for buses detected on a link according to a priority level associated with the individual vehicle. To enable this, SCOOT must receive a priority level together with other information about the detection of a bus. This priority level (or “bus importance factor”) is then used to determine what priority can be given for the bus. Bus priority levels are graded from 0 to 6.

The mechanism for determining the priority level for a given bus is located outside SCOOT. SCOOT receives the priority level, but does not know how this was produced. For an AVL system, the priority level may depend on the behaviour of the bus relative to a headway or timetable. For a Selective Vehicle Detector (SVD) system, there may be no information available about the identity of the bus, so a fixed priority level could be defined for all buses detected on a certain link or on a specific detector.

3 BENEFITS OF BUS PRIORITY

3.1 Benefits of recalls and extensions

The benefit to buses gained through providing SCOOT priority without stage skipping varies considerably, and is dependent on the scope for increasing or decreasing the lengths of signal stages. At junctions where the non-priority stages are already at, or close to, their minimum length, there is little scope for providing priority through recalls. Assuming that stages are not running close to their minimum lengths, the benefits of priority are then very dependent on the traffic conditions. Reductions in delay as high as 50% were achieved when the degree of saturation is low. At high degrees of saturation, the reduction in delay is of the order of 5–10%. In extensive trials in London, reductions of delay of around four seconds per bus per junction were typical. The increase in delay to general traffic is similarly dependent on the degree of saturation. At low degrees of saturation the increase is small and insignificant, whereas at high degrees of saturation the increase in delay to general traffic can be large. The disruptive effect of providing priority by recalls is much greater than by using extensions. Giving recalls to buses on a side road can be particularly detrimental as it reduces the green time as well as disrupting the coordination along the main road.

The number of buses being given priority is also an important factor, particularly at higher degrees of saturation. Benefit per bus decreases as bus flow increases, owing to competing/conflicting priority calls, but total passenger benefit remains substantial at bus flows as high as 120 buses per hour per junction.

3.2 Benefits of stage skipping

The benefits of stage skipping arise in addition to those obtained through extensions and recalls. When restrictions are at their minimum level, stage skipping gives good benefits in the range of 2.5–6 seconds per bus per junction, depending on the junction and flow conditions. Typically, where the skipped roads are not too busy, the extra saving in delay owing to stage skipping averages about four seconds per bus. At junctions where the links being skipped are busy, the benefit may be as low as one second per bus even if the skipping is uninhibited. This low benefit can be attributed to the delays to buses caused by longer queues of general traffic.

On average, there is a small increase of about one second per vehicle in the delay to general traffic when stages are skipped. The main disbenefit is to traffic on the side road being skipped. At junctions where the links whose green is skipped are busy, it is necessary to use the stage skipping saturation parameter employed in SCOOT in order to avoid large increases in delay to general traffic.

3.3 Benefits of differential priority

Extensive simulation testing has been carried out in order to investigate the effects of providing differential priority. The study considered both bus services that run according to a fixed timetable and those that run according to a fixed headway (normally high frequency services). Some of the main findings were:
• For both fixed-headway and fixed-timetable services, the highest average reductions in journey time are given by strategies that provide priority to all buses. In general, the more buses that received priority the higher the average reduction in journey time.

• For both fixed-headway and fixed-timetable services, using differential priority generally minimises the increase in delay to other vehicles – which is greatest at the highest flow level.

• For fixed-headway services, there is no improvement to regularisation (standard deviation of headway) for non-differential priority strategies.

• The strategies that provide priority only to late buses improve regularity and reduce passenger wait time the most.

• For fixed-timetable services, non-differential strategies do provide good improvements to regularisation. However, the differential priority strategies provided the highest benefits.

4 NEW BUS PRIORITY DEVELOPMENTS
The latest development in SCOOT is designed to take advantage of the new technical innovations introduced into London; namely iBus, which allows for multiple detections on a link; and the changes in bus operations, which should reduce the variability in bus dwell times. In particular, the bus priority logic in SCOOT has been enhanced to allow a cancel detector when the bus passes through the junction. The maximum value for the bus journey time has also been increased. These two developments provide for “predictive priority” where buses are initially detected earlier, possibly before reaching the bus stop. These developments are described in more detail below.

4.1 Cancel detection
In order for SCOOT to provide priority to buses, it is necessary for them to be detected some way before the stop line. SCOOT then models the bus travelling down the link and crossing the stop line using the configured journey time from the detector to the stop line, the modelled traffic queues on the link and the colour of the traffic signals. In practice, because of the variability of the actual behaviour of the bus and the queuing traffic, this modelling cannot be assumed to be perfect. When giving priority to buses by providing extensions, therefore, it is prudent to allow extra green time in order to ensure that the bus has crossed the stop line. The amount of this extra green time is determined by the value of the input data parameter BVARY. The setting of the BVARY parameter, however, currently constitutes something of a dilemma. A high value for BVARY would ensure that all buses given an extension would pass through on green; however, this would provide unnecessarily long green times on many occasions, resulting in higher delays to traffic on opposing stages. Conversely, a low value of BVARY may lead to some buses not getting through on the green.

The introduction of a cancel detector should help to overcome this dilemma. The cancel detector will allow an extension to be terminated when a bus has crossed the stop line. It will therefore be possible to set a high value for BVARY, which reduces the chance of a bus being given an extension but then in fact being stopped by the lights. Once the indication that the bus has reached the cancel detector is received, then the stage will be terminated – avoiding the unnecessary extra green time being given to the bus, and so reducing disruption to other traffic.

4.2 Long journey time
The original SCOOT bus priority logic was based on the assumption of immediate implementation – i.e. that for maximum efficiency, bus priority should be given as soon as a bus is detected subject to constraints such as BAUTH (maximum extension allowed) and BESAT (degree of saturation constraint). So if a bus is detected during green, an extension may be granted which is implemented by extending the current green. Conversely, if a bus is detected during red a recall is implemented as soon as possible, with stages being shortened and run in succession until a stage is reached which is green to the bus. Then, the stage remains green until the bus has left the link.

For shorter journey times, the above assumption is valid and results in priority being given as soon as possible for a bus. For longer journey times, however, the assumption may not be valid, and this can result in very long greens or in priority not being given.

The original logic also made the assumption that when a bus is detected in red, a recall will always be beneficial. No check was made as to when the next green would start, and it was possible that the recall would cause the green to start earlier than was required. The assumption was reasonable for situations with short journey times, as there would be at most a few seconds of wasted green. For longer journey times, however, the original logic could result in a large amount of wasted green time.

The SCOOT logic has now been modified so that it will operate satisfactorily with long journey times. This has been accomplished by introducing a system of delayed implementation. This means that if the bus is too far away, the control system will delay the preparation of the extension or recall until it is at the correct stage in the cycle for the logic to operate as intended. The extension or recall will then be implemented when it can be used by the bus, thus avoiding wasted green time.

4.3 Predictive priority
The development to allow multiple detection points, cancel detectors and long journey times should make it possible to give higher levels of priority to buses. By detecting the bus earlier, possibly before the bus stop, the number of times that an extension can be given will be increased. Earlier detection might also increase the benefit owing to a recall. There will be some inefficiency introduced owing to the increased variability in journey time, which needs to include any bus-stop dwell time. As long as the variability in the bus-stop dwell time is not too high, this should be mitigated by the addition of a second downstream detector and a cancel detector. The method of initial detection of the bus before it reaches the bus stop has been termed “predictive priority”.

Selected papers: Quantifying the benefits of new bus priority logic in SCOOT
5 THE BENEFITS OF NEW BUS PRIORITY DEVELOPMENT

An evaluation of the benefits of the new development is currently ongoing. Initially, the new facilities are being evaluated using the VISSIM micro-simulation interfaced to the SCOOT UTC system. These will then be followed by on-street trials.

5.1 The SCOOT–VISSIM link

TRL has developed an interface between VISSIM and the SCOOT kernel. SCOOT is able to control the traffic signals in VISSIM in the same way that it would control traffic signals on street, except that the system has been modified by the removal of time constraints so that it can run faster than real time.

The transmission lag between the street and the SCOOT kernel is modelled by holding back data for the required time, and SCOOT is informed of the length of the delay.

5.2 Farringdon Road/Rosebury Avenue junction

Initial studies were carried out on a network that modelled operations on a section of Farringdon Road in London (node N03/031). Additional benefits of between three and six seconds per bus, depending on the settings, were noted from using an upstream detector compared with a downstream detector. Surprisingly, other vehicles also benefited by up to seven seconds per vehicle on some settings. It was realised that this was because the vehicles had to queue behind the bus when it was stopped, and so the extra green time offered to the buses when using the upstream detector was also of use to the cars behind the bus.

While being a particularly good intersection at which to demonstrate the benefits of upstream detection, it was realised that this would not be a good junction on which to try out the cancel detector, as this would cut short the extension once the bus had passed – leaving the cars that had been waiting behind waiting even longer.

Therefore, work was started on another network, set up to model Balls Pond Road, where the other traffic was able to pass the bus while it was stopped at the bus stop.

5.3 Balls Pond Road

A VISSIM model was set up to mimic Balls Pond Road in London. Three junctions were set up: N03/018, N04/066 and N04/046. Therefore, if the bus priority were to result in reduced coordination, the adverse effect on the traffic would be felt.

Figure 5 shows a node diagram of the three junctions set up in the VISSIM model.

Initially, a study to find the ideal location of the cancel detector for central extensions was carried out on link N03/018c (see Section 5.4), and some different settings were tested on the same link (see Section 5.5). Future work will entail granting priority to a combination of links around junction N04/066. Preliminary results are discussed in Section 5.6.

5.4 Location of the cancel detector

When central extensions are used as opposed to local extensions, there is a transmission lag between the street and the SCOOT kernel. As a result, the ideal location for the cancel detector will not be at the stop line, because by the time SCOOT is informed the bus is already five seconds ahead. To determine the best place a series of simulations were carried out, with the cancel detector placed at different locations along the link.

In order to make the best location for the cancel detector easy to spot, the settings for these simulations were chosen in order to exaggerate the effect of the cancel detector. The opposing flows to the priority link were large, the saturation target for extensions was 130% and the maximum extension (BAUTH) was 30 seconds. As a result, when extensions were granted they often had a severe effect on the opposing traffic streams.

Figure 5: Node diagram
The downstream detector was placed six seconds, 41.7 m, from the stop line, so when it was in use the scope for extensions was small, ensuring that there was little disruption to other traffic. In contrast, the upstream detector was 99 m from the stop line and had a journey time (including a 20-second dwell time) of 43 seconds. Therefore, when the upstream detector was used, there were more extensions.

Figure 6 shows the delay to buses when an upstream detector is used in combination with a cancel detector. The resultant delay (shown by the blue line) is approximately constant until the detector is placed beyond 40 m of the bus stop. At this point, the cancel detector stops working effectively as it begins informing SCOOT that the bus has left the link before it actually has. As a result, the extension can end before the bus gets to the stop line. The delay to buses is therefore increased, to near what it would be if there was no bus priority at all (purple line). The only reason that the delay is lower than it would be with no bus priority is because the recalls are still operating correctly, as they are unaffected by the cancel detector.

In the scenario shown, the cancel detector (blue line) provides no additional benefits to the buses compared with using the upstream detector alone (orange line). However, with different settings, the buses can benefit as the cancel detector reduces the amount of wasted green time. We show this in a later study (see Section 5.5).

Using an upstream detector, with or without a cancel detector, provides greater savings to buses than a downstream detector (green line).

Figure 7 shows the delay to other vehicles over the whole network. When the cancel detector is at the stop line, the delays are only slightly less than without the cancel detector; however, as the cancel detector is placed further back from the stop line, the delay to private vehicles decreases. There is a plateau region between 30 m and 45 m from the stop line, before a sharp drop in delay when the cancel detector is further than 50 m from the stop line.
5.6 Priority on more than one arm

Using junction N04/066 as shown in Figure 5, we provided priority to several arms at once. Preliminary results show that if the maximum extension is set to 30 seconds, target saturation for extensions is set at 130% and the upstream detector is in use, the other traffic can suffer badly with little or no extra benefit to buses. This shows that care must be taken when using upstream detection: even the cancel detector could not mitigate the results in this case.

However, choosing a lower saturation target of 100% and only allowing up to 15 seconds’ extension did allow buses to receive priority without causing great disbenefit to other vehicles – although the results were not compelling enough to suggest that the upstream and cancel detector performed better than downstream alone.

Our results in this area – very mixed as they were – are preliminary only. Even when only two approaches, both green during the same stage, were granted priority, the results often suggested that downstream detection was the best option.

In order to determine when predictive priority can be used in several approaches, and what settings should be used, more simulations (possibly using our simpler in-house SCOOT simulation program, STEP) and/or on-street trials will be required.

### Table 1: Results using more realistic settings

<table>
<thead>
<tr>
<th>Bus priority</th>
<th>Bus detectors</th>
<th>BVARY</th>
<th>Delay to buses on priority link</th>
<th>Delay to other vehicles over network</th>
</tr>
</thead>
<tbody>
<tr>
<td>OFF</td>
<td>None</td>
<td>N/A</td>
<td>52.9</td>
<td>74.3</td>
</tr>
<tr>
<td>ON</td>
<td>Downstream</td>
<td>2</td>
<td>46.6</td>
<td>75.6</td>
</tr>
<tr>
<td>ON</td>
<td>Upstream</td>
<td>2</td>
<td>44.2</td>
<td>76.5</td>
</tr>
<tr>
<td>ON</td>
<td>Upstream</td>
<td>6</td>
<td>44.5</td>
<td>77.1</td>
</tr>
<tr>
<td>ON</td>
<td>Upstream</td>
<td>10</td>
<td>43.5</td>
<td>76.9</td>
</tr>
<tr>
<td>ON</td>
<td>Up and cancel</td>
<td>2</td>
<td>43.4</td>
<td>76.6</td>
</tr>
<tr>
<td>ON</td>
<td>Up and cancel</td>
<td>6</td>
<td>42.3</td>
<td>76.3</td>
</tr>
<tr>
<td>ON</td>
<td>Up and cancel</td>
<td>10</td>
<td>43.8</td>
<td>76.9</td>
</tr>
</tbody>
</table>

The reason for this shape of graph is the transmission lag associated with central extensions. When the cancel detector is close to the stop line, the extension is held a few seconds longer than necessary – hence the larger delay to other vehicles. Looking at both graphs, it can be seen that the optimum location for a cancel detector is between 30 m and 40 m from the stop line. Further away from the stop line the extensions are cut short, and the delays to other vehicles are as low as they would be with no bus priority.

5.5 Evaluating the benefits

Having established the ideal position of the cancel detector, we proceeded to evaluate the benefits of predictive priority using more realistic settings.

The maximum extension was reduced to 20 seconds, and the opposing flows were reduced by a quarter so that the links were no longer oversaturated. The results are summarised in Table 1. Now that the maximum extension has been reduced, and the opposing links are no longer oversaturated, the additional delay when the upstream detector is in use is reduced. The buses still benefit from the use of the upstream detector, but only by two to three seconds compared with the downstream detector.

The cancel detector saves an extra two seconds per bus when the BVARY is 6, as less green time is wasted and so more green is available for the next bus. However, this effect is not apparent when BVARY is 10. This may be owing to fewer extensions being granted, as the extra journey time would bring the extension over the maximum of 20 seconds.
6 CONCLUSIONS

The new facilities in SCOOT enable a bus to be detected much further from the stop line than previously advised. This is especially useful if there is a bus stop near the stop line. With the new logic, the detector can be placed upstream of the bus stop, allowing SCOOT to grant longer extensions whereas previously, with a downstream detector, it would have been informed about the bus too late to grant an extension.

We have shown good benefits to buses, but have shown that the other vehicles can suffer delays if the settings are too generous to buses. If the link being granted priority is a main link crossing small side roads, this is unlikely to have a large effect; however, if the link being granted priority is a side road, the main road can suffer large delays if long extensions are granted and/or a large target extension saturation is set. Similarly, if priority is being granted on more than one arm, the settings must not allow too many long extensions. Current advice is to avoid predictive priority on multiple approaches until on-street trials have been completed, and the limits of use and optimum settings can be determined.

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**Iain Knight** is the Technical Lead of the Integrated Safety Team, with 14 years’ experience at TRL. He also has prior experience in the test and development of braking systems for cars with a tier one supplier. His core expertise is in vehicle primary safety, the investigation of accidents and the analysis of accident databases. He has presented evidence from his work at international conferences and committees, as well as directly to decision makers in government and industry. His experience includes research into accident cause and effect; the potential of longer, heavier goods vehicles; braking, handling, rollover stability and the performance of safety features such as Electronic Stability Control (ESC); Collision Mitigation Braking Systems (CMBS); Brake Assist Systems (BAS); and underrun protection. He has led projects to develop a primary safety rating scheme for new vehicles – including test procedures for braking, handling, lighting, visibility and ergonomics – as well as leading recent projects to develop regulatory test procedures for agricultural vehicle braking and brake assist. He has received formal training from the UK Vehicle Inspectorate (now VOSA) on the examination of vehicles.
INTRODUCTION
The need for evidence-based policy decisions has developed during recent years. There are a number of techniques that are available to determine the impact of different policy options or proposed legislative changes. The extent of the evidence provided for regulatory change is often directly related to the proposal under consideration.

This paper discusses the issues surrounding the generation of evidence for regulatory change. A number of examples of recent benefit studies are used to highlight the issues. Smith et al. (2008) developed a methodology for assessing the benefits of active safety systems for Powered Two-Wheelers (PTWs). Information from this study, which was funded by the UK Department for Transport (DfT), is used as a starting point to stimulate and inform further debate, and the future improvement of the research and policy making community’s efforts to improve the evidence on which decisions are based.

ABSTRACT: Policy makers require evidence of the costs and benefits of a particular safety measure in order to inform their views in policy decisions. These analyses are often required in a short period of time, with limited research budgets. Increasingly, the measures considered are advanced control systems intended to help drivers avoid a collision. It is inherently difficult to accurately assess the casualty effects of such systems, and this, combined with resource constraints, often results in a wide range of conflicting predictions based on different assumptions, simplifications and analytical techniques. Substantial variation in the presentation of results can make it difficult for researchers to directly compare different studies. In turn, this makes it difficult for policy makers to be confident of the right approach. As a result, studies of very different levels of reliability are often given equal weight in policy debates – risking the possibility of less than optimal implementation of new safety features.

This paper describes the development of a methodology intended to allow a preliminary assessment of the potential benefits of advanced safety systems to be undertaken in a consistent and objective manner. An initial methodology was developed, based on literature and expert opinion, and then tested and refined by applying it to an assessment of existing studies of advanced braking systems for motorcycles.

The research was, therefore, limited to a relatively narrow scope. However, the potential for the method to be expanded in future was explored in order to assess the possibility of providing a generic methodology to guide policy makers and researchers alike regarding the:

- Scientific confidence required from a new study, or implied by existing analyses
- Suitability of different analysis techniques for the measures being assessed
- Consistent presentation of results in order to aid subsequent comparison of different studies
IDENTIFICATION OF THE PROBLEM

Historically, safety improvements have been developed quite slowly. For example, the European Frontal Impact Directive came into force in the mid-1990s, but it was supported by research and development going back to the 1970s/80s. The rapid development of new active safety systems, coupled with the fact that safety has become a strong selling point for manufacturers and consumers, means that governments are often under pressure to regulate much more quickly than before. For example, the very first Collision Mitigation Braking Systems (CMBS) came on the market only a few years ago, and currently are only available as options on a small number of high-end passenger cars and one or two truck models. However, it is proposed that they are made mandatory on all new heavy vehicles by 2013. This means that impact assessments for the regulations must be completed at a time when little, if any, accident data for vehicles equipped with such systems exist. This situation is further complicated when assessing the benefits of primary safety (accident avoidance) technologies. Unlike secondary safety (severity reduction) measures, success in these cases means that there is no accident – and therefore no accident data with which to compare the outcome before and after implementing the measure. These factors combine to result in considerable variation in the quality/depth of the analyses produced.

However, each level of analysis has its place with respect to the change in legislation being proposed. For example, well-supported proposals, such as the introduction of Electronic Stability Control (ESC) for heavy goods vehicles (HGVs) may require only minimal evidence in order to be successful. However, more controversial proposals such as those for Brake Assistance Systems (BAS), Daytime Running Lights (DRL) and Advanced Emergency Braking Systems (AEBS) have been supported with a wide variety of studies of differing scientific quality/depth. The scientific quality of benefit assessments is influenced by a number of factors, such as the availability of data upon which to base the assessment and suitable information about the effect of the proposal.

Many benefit assessments consider the potential effect of each safety measure on its own. However, in many cases, a number of different measures could influence the same groups of casualties. One example of this is the proposal of the European Commission to mandate AEBS. These systems have an automated braking function, the benefits of which can be predicted using existing accident data. However, it is anticipated that the production systems will include functions such as adaptive cruise control, forward collision warning and pre-impact adaptive restraint systems, which will not be mandatory. These types of system are already fitted to some vehicles, and will be fitted to more vehicles than are equipped with AEBS. Therefore, the fleet penetration of such systems will be ahead of AEBS, thus reducing the benefits of the AEBS function itself – a factor not accounted for in the benefits study undertaken. There are also potential effects on completely separate systems such as anti-whiplash seats, because AEBS will influence the frequency/severity of rear impacts.

DEVELOPMENT OF A METHODOLOGY

Smith et al. (2008) developed a generic methodology to evaluate the casualty benefits of advanced safety systems for PTWs. The research was funded by the UK DfT and the objectives of the methodology were to:

- Identify the most suitable and cost-effective method of providing evidence of a safety benefit for a range of motorcycle safety systems
- Include provision to estimate the potential for accident avoidance or injury mitigation using accident statistics or in-depth accident data, by identifying causation factors and then assessing the likely impact of advanced safety systems for relevant accidents

In addition to achieving these two objectives, it should also be possible to use the methodology developed to appraise critically research that has already been completed. Although these objectives are specific to assessing advanced safety systems for PTWs, the principles of the methodology can be applied to all safety measures across all types of vehicle. The following section describes the methodology developed by Smith et al. (2008). The methodology consists of three main steps, and an overview is shown in Figure 1.
The methodology starts by identifying the burden of proof that the evidence must satisfy, for example:

- Policy makers are sometimes confronted with a large number of proposals for a huge range of potential new safety measures. In this type of situation, it is considered useful to have an initial “filter” in order to help identify which measures warrant further investigation. It is not necessary to have rigorous proof of the exact effects, merely a broad indication of the potential. This sort of requirement is considered to represent a very low burden of proof.

- By contrast, if a major new safety regulation is planned that is likely to have a high cost, carries a risk of adverse effects on other policy areas – e.g. greenhouse gas (GHG) emissions – and/or is likely to encounter significant opposition, then very rigorous supporting analysis, which accurately and incontrovertibly demonstrates the effects, might be required. This would be considered to require a very high burden of proof.

**Step 1 – preliminary filter**

Step 1 of the methodology is the definition of a preliminary filter that can be applied to accident data. The primary objective of this step is to define groups of accidents, against which an initial evaluation of the potential benefit of a safety measure can be assessed. Additionally, a secondary objective is to allow the most frequent or most severe groups of accidents to be identified in order to inform the development of new safety systems.

Step 1 can be used for quick stand-alone comparisons for a range of potential safety measures. It could also be used to rapidly assess how relevant proposals from one country are to the vehicle and accident population in another country, or as a quick reference to assess the maximum potential benefit of a new safety system. For example, such a filter was developed as part of a review of heavy vehicle safety priorities – Smith et al. (2007). During a subsequent policy debate about the possible extension of the scope of United Nations Economic Commission for Europe Regulation 66 (UNECE R66) to double-deck buses and minibuses, this filter was used, in a matter of minutes, to identify the fact that, in the UK, large bus/coach occupant casualties (i.e. including those in single-deck vehicles already included in R66) in rollover accidents were the 157th most important casualty group involving heavy vehicles (out of a total 244 groups), with an annual casualty valuation of £1.8 million. Thus, extending the scope of R66 to double-deck vehicles was considered unlikely to be cost-effective in the UK unless the measure could be implemented very cheaply. A similarly quick analysis found that extension to minibuses had much greater potential.

In order to carry out Step 1, a definition of the system specification is required. This should set out the functional requirements of the system under consideration, allowing the casualty groups that could be affected to be identified. When setting up a preliminary filter, there are three main considerations:

**What is an appropriate dataset?**

It is recommended that the dataset is a national sample, or is known to be representative of the national sample (evidence of how the dataset represents the national population should also be presented). The data should cover a period of at least one year – ideally, an average of a number of years – and be as up to date as possible.

**How should accidents be grouped in the filter?**

The grouping of accidents can be influenced by the vehicle type to which the safety system is to be fitted, as well as the type(s) of system under consideration. The following aspects should be considered, and any limitations of the grouping should be noted:

- The grouping should allow comparison of accident types and be independent of the detailed functionality of the safety systems.
- The grouping should be appropriate to the systems being reviewed. It should allow differentiation between different systems where possible (e.g. a braking system could influence a small proportion of a large number of groups, whereas a cornering stability control system might influence only one or two groups).
- The groups should be mutually exclusive to avoid double counting where multiple groups are affected by a system.
- All casualties within the accidents should be included if possible, i.e. casualties in the vehicle to which the system is to be fitted, casualties in the opponent vehicle (first impact) and any other casualties in the accident (including pedestrians).

**How will the groups be compared?**

The accident groups can be compared using a number of different measures that reflect the frequency and/or severity of the casualties (e.g. number of casualties, number of fatalities, monetary valuation associated with the prevention of casualties).

The output from this step is an estimate of the maximum potential benefit of the system. The estimate will be the sum of the casualty groups that can potentially be affected. Although a relatively crude assessment, the preliminary filter will identify if there are tens or thousands of casualties that could be addressed by the system.

Additionally, the preliminary filter will produce groups of casualties. This enables a reference tool for policy makers and researchers to identify where resources should be targeted. For example, in 2005 there were no fatally injured riders of PTWs with engine capacity less than 50 cc in collision with a minibus, and only three seriously injured. In comparison, there were 101 fatally and 818 seriously injured PTW riders in accidents where a PTW with engine capacity more than 500 cc was the only vehicle involved.
Step 2 – target population

Step 2 of the methodology is intended to identify more accurately the accidents that could be affected by the system under consideration (defined as the target population). The target population is specific to the safety system and should be as accurately defined as possible, including causation factors where required.

The term “target population” can be used in a variety of ways, for example:

- The number of casualties that could be prevented by a system that is 100% effective in each of the accident situations it is intended to influence, e.g. works in all weather conditions, at all speeds and accounts for driver behaviours
- Casualties within a group of accidents that could potentially be influenced by the measure, e.g. head-on collisions, rear-end shunts

This measure is one that is often used differently in different studies. For example, the number of detailed data fields (e.g. impact location, speed, driver behaviour factors) that are used to identify it can vary considerably between studies, often leading to misunderstandings and difficulties for policy makers comparing the results of different studies. There is, therefore, a need for a more common understanding of what is meant by the term. For the purpose of this methodology, the target population is defined as the number of casualties that could be prevented by a system that is 100% effective in each of the accident situations it is intended to influence. For example, for a forward-collision warning system it would be all casualties where the impact location was the front of the vehicle, the vehicle was moving forward prior to impact and the driver/rider was considered to have been inattentive. This number can also be expressed as a percentage of all accidents.

To carry out Step 2 of the methodology, a detailed specification of the system and appropriate accident data are required. There are five aspects to be considered in this step:

(i) In what situations is the system intended to be of influence?

In order to define the target population, it is necessary to understand how the system operates and the situations where it is intended to be of influence. There should be a written description included in the report.

(ii) What are the relevant types of accident and vehicle for the system being assessed?

The definition of each accident type and relevant vehicles should follow these guidelines:

- The accident types that could be influenced by the safety system should be identified in as detailed a manner as possible for the data source being used. The definition should include criteria that will allow the accidents relevant to the specific system to be identified. For example, head-on collisions can have a number of different causative factors (inattention of one or more of the drivers involved, impairment of the rider/driver, etc.). It is recommended that the accident type is defined by the impact configuration (where appropriate) as well as at least one causation factor such as rider/driver behaviour (where appropriate). There may be multiple types of accident that could be influenced.

- It is often appropriate to define the target population in relation to the vehicle type to which the system is to be fitted (e.g. HGV, passenger car, PTW). The composition of the vehicle fleet can be very different when comparing different countries. Sometimes it may be appropriate to define the target population for a subset of one vehicle type. For example, when considering anti-lock braking systems (ABS) for PTWs, the target population can be separated by engine capacity – PTW less than 50 cc and PTW greater than 50 cc – because small urban mopeds are involved in different types of accidents to larger, more powerful motorcycles.

(iii) What information is available to estimate the target population?

The target population can be estimated based on different sources:

- Accident data will allow the most flexibility in defining the target population (within the constraints of the data sample being used). This is the preferred method for defining the target population.
- Existing scientific literature and benefit studies can also be used, but the definition of the target population is likely to vary between different studies and if no studies are available for the required country the answer could be misleading – particularly where patterns of use vary considerably between different countries, as is the case for PTW accidents.

(iv) How can these relevant accidents be identified in the accident data?

Does a national data sample have a sufficient level of detail? Are causation data and pre-impact information available to identify the relevant accidents in the national data sample?

- If it is not possible to identify the relevant accidents using a national data sample, is there an in-depth study available that has appropriate detail and represents the national sample appropriately (at the level of detail required)? If so, the use of a more detailed accident database should be considered. However, it is necessary to identify the limitations of such an approach. One of the most important limitations will be related to the representativeness of the data sample. Any assumptions must be reported – for example, if the representativeness is not known at the level of detail required (e.g. rider behaviour factors) but is known at a higher level (e.g. types of casualties and vehicles involved), it can be reasonably assumed that the rider behaviour data are also representative. However, such assumptions must be stated clearly in the report of the analysis.
Where possible, the target population should be expressed for each level of casualty severity as a proportion of all casualties of that severity. However, in some cases it is not possible to identify all casualties of a particular severity. For example, official statistics for the EU-27 (the 27 nations of the European Union) provide the number of fatalities and the number of all accidents, but not the number of serious and slight casualties. Therefore, the target population should also be shown as a proportion of all accidents (of all severities) within the sample. This will assist direct comparisons across different countries. However, if using the target population as a proportion of all accidents, care should be taken when translating results from one country to the accident numbers from another country because of variations in the definitions used for the casualty severities. A table showing how that particular data should be presented is shown in Table 1. Figures that may not be readily available in all countries/regions are identified by an asterisk.

### Table 1: Example presentation of target population data

<table>
<thead>
<tr>
<th></th>
<th>Fatal</th>
<th>Serious</th>
<th>Slight</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>Target population (number of casualties)</td>
<td>123</td>
<td>467</td>
<td>1252</td>
<td>1842</td>
</tr>
<tr>
<td>Total number of GB casualties (by severity)</td>
<td>3512</td>
<td>24 571*</td>
<td>256 830*</td>
<td>284 913*</td>
</tr>
<tr>
<td>Total number of GB accidents</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>197 856</td>
</tr>
<tr>
<td>Target population (% of GB casualties by severity)</td>
<td>3.50%</td>
<td>1.90%*</td>
<td>0.48%*</td>
<td>0.65%*</td>
</tr>
<tr>
<td>Target population (% of all GB accidents)</td>
<td>0.06%</td>
<td>0.24%</td>
<td>0.63%</td>
<td>0.93%</td>
</tr>
</tbody>
</table>

* Data may not be readily available in all countries/regions.

- **What factors could influence the target population?** The target population can be defined in a number of ways. This could lead to the inclusion or exclusion of accidents where certain factors were involved. For example, should impaired drivers (e.g. those intoxicated through alcohol or drugs) be included in the target population? In general, accidents should only be excluded from the target population on the basis of this type of factor if it is clear that there is no chance that the measure under consideration will affect them. This will help to allow consistency in study approaches using different datasets – for example, from different countries. However, in some circumstances it will be appropriate to restrict the target population in this way, and wherever this occurs the restriction should be stated and the calculation of effectiveness that will be applied in Step 3 should be modified accordingly.

- **Are there any limitations with the criteria that have been used to define the target population?** Some data recorded in databases have inherent limitations. For example, the information required may frequently be unknown, or may rely on subjective assessments.

(v) **Have the correct accidents been identified?** It is possible that the criteria used to select a specific group of accidents could unintentionally return some non-relevant accidents. The analysis should be accompanied by some indication of confidence in the query that has been used. If the data source has written descriptions of the accidents, then these could be used. However, if there are no written descriptions then an alternative method should be considered – for example, cross-referencing to another database that does have written descriptions.

The output from Step 2 is the target population for the specific system that is being assessed. The target population is a group of accidents that are relevant to the system under consideration. This is the maximum potential benefit for the system, i.e. if it were 100% effective and the target population were to be equal to the expected benefit. In reality, most systems are not 100% effective at preventing the collisions/casualties for which they are designed, and thus Step 3 is required to more accurately quantify the expected benefits.

Where possible, the target population should be expressed for each level of casualty severity as a proportion of all casualties of that severity. However, in some cases it is not possible to identify all casualties of a particular severity. For example, official statistics for the EU-27 (the 27 nations of the European Union) provide the number of fatalities and the number of all accidents, but not the number of serious and slight casualties. Therefore, the target population should also be shown as a proportion of all accidents (of all severities) within the sample. This will assist direct comparisons across different countries. However, if using the target population as a proportion of all accidents, care should be taken when translating results from one country to the accident numbers from another country because of variations in the definitions used for the casualty severities. A table showing how that particular data should be presented is shown in Table 1. Figures that may not be readily available in all countries/regions are identified by an asterisk.

### Step 3 – effectiveness

Step 3 of the methodology is intended to refine the benefit estimate that was defined in Step 2 – i.e. to translate the analysis from the maximum possible benefit (target population) to a realistic likely benefit. The main objective of this step is to determine how effective the system will be for preventing the casualties/accidents that make up the target population. There are a number of different methods for determining/identifying the effectiveness of the system, and this step is intended to help identify the most appropriate method for the quality of estimate/burden of proof required. It is possible to define the effectiveness of the system under consideration without defining the target population in Step 2. The inputs into Step 3 of the methodology can depend on the approach taken, but can include:

- Accident data
- Literature
- System specification
- Quality requirements
- Test/trial results

In order to determine the effectiveness of the system in the most appropriate manner, the following aspects require consideration.
What burden of proof is required?
The burden of proof required should be classified on a scale from very low to very high. Step 3 is typically only required when the burden of proof is medium or higher – e.g. relating to proposals for voluntary or mandatory fitment. Figure 2 summarises how to determine the most appropriate method. Additional guidelines are provided below.

What is the most appropriate assessment method for the information available?
The selection of the method to be used will be based on the burden of proof required, the availability of the system being assessed, constraints on cost and time and the availability of accident data and literature. The main types of method that can be used for determining/estimating the effectiveness of the system are:

- **Predictive studies**, which examine accidents where vehicles were not equipped with the specific feature under consideration and make calculations and/or judgements to assess whether the accident would have been avoided or mitigated if the safety feature had been present. There are a number of different methods that can be used when carrying out a predictive study. The most appropriate method will, again, be influenced by the burden of proof required and budgetary/time constraints.

- **Parameter-based predictive studies**, which are the most straightforward, and are likely to be appropriate for a medium burden of proof. This type of study is an extension of the target population exercise described in Step 2, and involves interrogating an accident database to identify what burden of proof is required?
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![Figure 2: Identification of appropriate method for determining effectiveness](image-url)
in more detail the casualties for which a system is likely to be effective. If a forward collision warning system was assessed, the target population might be all front-to-rear shunt collisions where the vehicle to which the system is to be fitted approached from the rear. The effectiveness calculation might further restrict the target population in order to exclude accidents where the driver of the vehicle of interest was impaired, accidents on a bend or those that occurred in severe weather conditions where the system was known not to function well. The quality of this type of analysis will not only depend upon the detail, accuracy and representativeness of the data source used, but will also require clear definitions of the functional performance of the system under test and a specification of any assumptions made to overcome limitations in the data.

• **Case-by-case analysis** involves the detailed review, reconstruction and prediction of effects in a number of individual accidents. The predictions can be made in a number of ways:

  i) An assessment of the effectiveness of the safety system can be made for each accident case identified based on the information available and engineering judgments. Again, the quality of this assessment can be influenced by the source of the data. If the cases have been reconstructed based on the sequence of events, the evidence left at the scene (e.g. tyre marks) and mathematical calculations (e.g. police accident reconstruction), there is more information available than what may be available from a limited number of database fields. The method can be made less subjective by providing guidelines that define when the system is expected to be effective. Weighting of the assessment with estimates of the probability of effectiveness (e.g. “definitely”, “probably” or “maybe”) can also reduce the subjectivity of the assessment. This method is likely to be appropriate for a high burden of proof (e.g. proposal for mandatory regulation of a moderately costly system).

  ii) Mathematical modelling can be used on a case-by-case basis, and is less subjective than the method described above. This procedure involves creating a computer model of an accident and simulating the outcome with the fitting of the safety system. Such an approach has the advantage of being fully objective but is more complex and time-consuming, and, because it is firmly rule-based, can miss some more subtle factors that influence outcomes. This method is likely to be appropriate when a high burden of proof is required.

A limitation of both techniques above is that it is difficult to rigorously include driver behaviour factors associated with the new system in the assessment of its effectiveness. Particularly for primary safety systems, it can be easy for critics to argue that the results are not valid because the system would induce a behavioural change that would reduce or eliminate the predicted benefits. Where the highest burden of proof is required, this limitation can be overcome through the use of physical trials involving ordinary drivers as subjects. These can take the form of simulator trials, track trials or field operational trials. This method can allow for human-factor issues to be combined with the accident data assessment; however, the reliability of the data is dependent on the assumptions made and the experimental methods used.

• **Retrospective studies** treat the feature under investigation as a risk factor, and use statistical methods to compare the relative risk of accidents in real-world accident data where vehicles can be identified that both do and do not have the relevant safety feature fitted. Where such an approach is possible, it has the most potential for providing a rigorous and defendable outcome because it seeks to objectively measure the actual effect on real vehicles in service with real drivers, thus accounting for many of the factors that can confound predictive studies. The size of the sample will have a strong effect on whether statistically significant conclusions can be drawn and the analytical design, particularly the control of confounding factors (e.g. systematic biases such as age of driver), will strongly affect the quality of the results.

**Is the system on the market?**

Whether the system is on the market, or available for trials, will influence the type of analysis that can be completed:

• **No** – If the system is not on the market, or at least not in significant numbers, then the estimation of effectiveness is restricted to a predictive study.

• **Yes** – If the system is on the market, then either a retrospective study or a predictive study – or both – can be carried out depending on the burden of proof required, analytical design factors and budgetary constraints for completing the analysis.

**What sources of information are available for determining the effectiveness?**

• **Literature**, which could include the findings from a range of studies that have already been carried out; these could have determined the effectiveness of the system under consideration. The findings from other studies should be reviewed critically, and any assumptions made should be identified in order to determine whether the effectiveness quoted is appropriate for the target population. The use of multiple sources is recommended, identifying where there is agreement or differences between studies. It may be necessary to define a range of effectiveness if there is no consensus in the literature, and the logic used to define this range should be reported. Where sufficient detail exists, a formal “meta-analysis” can be undertaken. This essentially involves calculating a statistical weighted mean of the effects identified by the previous studies. However, this can require substantial time and effort and requires the data in the literature to be well reported in considerable detail.
• **Specific research studies** can be used as a substitute for accident data, and can include field operational trials or questionnaire surveys to compare the accident involvement of equipped and unequipped vehicles and estimate the relative change in risk for equipped vehicles.

• **Accident data** can be used in order to allow either predictive or retrospective studies to be considered. The data sources used will be influenced by the burden of proof required, the type of analysis and also the function that the system is intended to achieve. For example, a parameter-based predictive analysis for assessing the benefits of improved helmets is likely to require a different source of data to a case-by-case predictive analysis of an advanced braking system. Retrospective analyses have different requirements again, and are typically based on national accident data.

• **Vehicle equipment data** can be used to identify whether the specific vehicles recorded in the accident data are fitted with a specific safety system. This type of information is an essential prerequisite of retrospective analyses.

• **Exposure data**, or the use of an induced exposure technique, are required in order to allow the probability of an accident occurring to be determined when carrying out a retrospective analysis.

The output from Step 3 is an estimate of system effectiveness that is relevant to the target population that was defined in Step 2. This can then be applied to the target population in order to estimate the casualty benefits for the safety system.

The estimated benefits should be clearly expressed as a percentage of the target population (so that it can be seen how effective the system is at addressing the intended group of accidents) and as a percentage of all accidents. In particular, the latter measure is important for comparison with other studies, and to provide the context for the predicted casualty benefit.

The estimated casualty benefits can be combined with vehicle registration data, casualty valuation information and details of the costs of the system in order to produce a full cost-benefit analysis. Defining procedures or guidelines for the generation of cost–benefit analyses was beyond the scope of this project. However, it is possible to logically assess the types of accident where advanced braking systems are more likely to have an influence – e.g. accidents at junctions where the PTW is travelling ahead, and single-vehicle accidents involving loss of control on a bend – and then quantify the number of casualties occurring in these “more likely” accident types. Such an assessment will be imperfect because not all of these casualties will be influenced by the technology, and there will also be other casualty groups that have been excluded but that may be influenced. However, it could give a closer indication than considering “all” accidents only.

A preliminary filter was developed based on a three-year sample of national road accident data (STATS19). The PTW casualties were grouped by the type of PTW being ridden (i.e. <50 cc, 50–125 cc, 125–500 cc and >500 cc) and the number of vehicles involved in the accident (single-vehicle vs multi-vehicle). Further categorisation is based on criteria such as: where the accident occurred (at a junction or not); whether there was loss of control; the first point of impact on the motorcycle; and what manoeuvre the PTW was making. Table 2 shows an example of the data that can be obtained by using the preliminary filter.

Ideally, the target population for all three braking systems would be any accident where the vehicle braked. Unfortunately, this cannot be identified from the available data. Therefore, the only rigorously acceptable target population is all casualties. The preliminary filter has been used to compare the relative sizes of the different casualty groups. It can be seen that the greatest benefits would appear to lie with larger motorcycles, simply because of their greater degree of involvement.

A more subjective approach can be used in order to try to get a more realistic target population. An upper estimate was based on excluding accidents where the PTW was waiting or

**APPLICATION OF THE METHODOLOGY**

Smith et al. (2008) applied the proposed methodology to assess the potential benefits of advanced braking systems for PTWs. The methodology was applied for three systems:

• **Anti-lock braking systems (ABS)**
• **Combined braking systems (CBS)**
• **Brake assist systems (BAS)**

This paper describes the information collated for the assessment of ABS as an example of how the methodology can be applied. The assessment of the potential benefits of ABS was restricted (by available budget) to the use of existing information only, i.e. mainly literature supplemented by limited analysis of existing accident data.

**Step 1 – preliminary filter**

The preliminary filter is intended to be used to identify casualty groups that could potentially be affected by the technology under consideration. However, ABS can influence a broad range of casualty groups to varying extents. Using this tool, therefore, it is only possible to generate a coarse estimate of the target population for braking systems. However, analysis according to the type of PTW involved could provide an insight into the best place to target the technology. Additionally, it is possible to logically assess the types of accident where advanced braking systems are more likely to have an influence – e.g. accidents at junctions where the PTW is travelling ahead, and single-vehicle accidents involving loss of control on a bend – and then quantify the number of casualties occurring in these “more likely” accident types. Such an assessment will be imperfect because not all of these casualties will be influenced by the technology, and there will also be other casualty groups that have been excluded but that may be influenced. However, it could give a closer indication than considering “all” accidents only.

The estimated benefits should be clearly expressed as a percentage of the target population.
Step 3 – effectiveness

According to the methodology described earlier, any new analysis of the potential benefit of ABS that is required to meet a high burden of proof could involve:

- Detailed definition of the performance characteristics of the system
- Predictive analyses, based on case-by-case review and reconstruction of on-the-spot and/or fatal cases in order to assess the influence of each system, with extrapolation of results to the national statistics (STATS19) for an estimate of national benefits
- Human-factor experiments on the test track to assess rider response to the system and identify any behavioural risks
- Identification of makes and model of PTW fitted with ABS (which is possible based on manufacturers’ literature, but is labour-intensive)
- Retrospective statistical analysis of the relative accident involvement of PTWs with and without the system

However, the scope of this research was limited to a review of existing literature. Table 4 summarises the findings from this review with respect to the effectiveness of ABS.
Table 4: Effectiveness of ABS as identified from the literature

<table>
<thead>
<tr>
<th>Effectiveness</th>
<th>Source</th>
<th>Region</th>
<th>Study type</th>
<th>Sample size</th>
</tr>
</thead>
<tbody>
<tr>
<td>Avoids 85% of downfall accidents where downfall occurs before initial impact</td>
<td>Baum <em>et al.</em> (2007), based on a retrospective study</td>
<td>Germany</td>
<td>Retrospective</td>
<td></td>
</tr>
<tr>
<td>Approximately 10% of motorbike accidents involving injury can be avoided or positively influenced</td>
<td>Sporner <em>et al.</em> (2000, 2002, 2004), cited in Gwehenberger <em>et al.</em> (2006), describe the dangers of braking with conventional braking systems and the avoidance potential through ABS in several studies based on the German Insurance Association (GDV) accident database (insurance claims)</td>
<td>Germany</td>
<td>Predictive</td>
<td></td>
</tr>
<tr>
<td>Avoids 8–17% of serious motorbike accidents</td>
<td>Gwehenberger <em>et al.</em> (2006): results of analysis of 200 serious accidents by Allianz Centre of Technology. Extrapolated to Germany as a whole, would result in around 100 deaths and more than 1000 serious injuries avoided a year</td>
<td>Germany</td>
<td>Predictive case-by-case; subjective</td>
<td>200 accidents</td>
</tr>
<tr>
<td>Net injury benefit 1–3% of all casualties</td>
<td>Kebschull and Zellner (2007) conducted a series of computer simulations based on data collected in the MAIDS (2004) and Hurt (1981) studies. Several configurations of ABS were simulated</td>
<td>USA and Europe</td>
<td>Predictive case-by-case; computer modelling</td>
<td>1800 accidents</td>
</tr>
<tr>
<td>Analysis of Austrian statistics showed that the benefit was comparable to the 55% stated by Sporner and Kramlich (2000)</td>
<td>Vavryn and Winkelbauer (2004)</td>
<td>Austria and Germany</td>
<td>Predictive</td>
<td></td>
</tr>
<tr>
<td>Increase in braking performance observed of novice and experienced test riders from 5.7ms(^2) to 7.7ms(^2) for novice riders and 6.6ms(^2) to 7.8ms(^2) for experienced riders</td>
<td>Vavryn and Winkelbauer (2004)</td>
<td>Austria</td>
<td>Human factors study</td>
<td>47 novice riders and 134 experienced riders</td>
</tr>
<tr>
<td>ABS reduces risk of riders being thrown from the bike. May lead to a reduction in forward collision and off-road crashes.</td>
<td>Bayly <em>et al.</em> (2006)</td>
<td>Australia</td>
<td>–</td>
<td></td>
</tr>
<tr>
<td>3% reduction in fatal and serious casualties</td>
<td>McCarthy and Chinn (1999)</td>
<td>UK</td>
<td>Retrospective</td>
<td></td>
</tr>
<tr>
<td>The effectiveness of ABS is currently under investigation as part of the PISA project. However, the report contains a ranking of various safety systems including ABS, CBS and BAS. Each system was given a score based on the potential influence on the accident outcome; however, this was not expressed as a percentage of the target population. ABS was given a score of 2.39</td>
<td>McCarthy <em>et al.</em> (2008): review of GBOTS/COST327 cases for PISA project</td>
<td>UK and Europe</td>
<td>Predictive case-by-case; subjective</td>
<td>60</td>
</tr>
</tbody>
</table>
To allow a detailed assessment of the benefit of fitting ABS, a measure of the effectiveness of the system for each level of accident severity is required. The literature review did not identify the effectiveness for PTW fatalities that could be applied to the target population. Therefore, the effectiveness of ABS used to identify the proportion of fatal casualties that could be prevented was based upon the information found from a review of the PSA (Powered Two Wheeler Integrated Safety) Fatal Accident Database. The development and analysis of this database was reported in McCarthy et al. (2008). However, the target population used in that case was not consistent with the other research identified, and therefore the data were re-analysed. From this additional review of fatal accidents, an effectiveness of between 8.8% and 35.7% was estimated, with a best estimate of effectiveness of 18%.

For serious casualties, the effectiveness used was based upon the estimates outlined in Gwehenberger et al. (2006) and McCarthy and Chinn (1999). Although Gwehenberger et al. (2006) include accidents of all severities, the sample is most representative in relation to serious casualties and states an effectiveness range of between 8% and 17%. McCarthy and Chinn (1999) state an effectiveness of 3% for fatal and serious casualties; however, their estimate is likely to be dominated by the effectiveness for serious casualties because the sample included only a relatively small number of fatalities. Therefore, 3% was selected as an approximate lower boundary for the effectiveness for serious casualties.

There was no research that specifically identified the effectiveness of ABS for slight casualties. However, Sporner and Kramlich (2000) – cited in Gwehenberger et al. (2006) – stated that ABS is effective in 10% of PTW accidents of all severity levels. In comparison, Kebschull and Zellner (2007) carried out a comprehensive study resulting in an overall effectiveness of between 1% and 3%. However, there were limitations associated with both studies, as described below.

Sporner and Kramlich (2000), cited in Vavryn and Winkelbauer (2004), undertook a study of 610 in-depth accident reports. Vavryn and Winkelbauer (2004) stated that Sporner and Kramlich's findings were that, on average:

"Approximately 55% of the motorcycle accidents could be avoided or at least positively influenced by ABS."

Multiple papers by Sporner et al. (2000, 2002 and 2004) are cited by Gwehenberger et al. (2006). Gwehenberger et al. (2006) stated that Sporner et al.’s findings were that:

"... approx. 10% of motorbike accidents involving bodily injuries can be avoided or at least positively influenced through ABS."

There appears to be some discrepancy between these two interpretations of an estimate of effectiveness from a single source. The only immediately apparent difference in the citations is the effectiveness estimate and the fact that Gwehenberger et al. reference their effectiveness as a proportion of PTW accidents involving bodily injury, whereas Vavryn and Winkelbauer's citation does not mention injury severity and so could refer to a specific severity level. However, it has not been possible to locate an English language version of the original paper in order to clarify the exact findings. The estimate of 10% is most likely to be applicable to the target population that has been defined for this study for the following reasons:

- The effectiveness of 55% was written as though it may be the effectiveness for a different target population
- Sporner was one of the authors of the Gwehenberger et al. (2006) paper, and would be expected to ensure that his previous research was cited correctly

Kebschull and Zellner (2007) found a relatively low effectiveness compared with other studies. A large percentage of the 900 European accidents investigated contained accidents which involved either no braking or braking with no loss of control, which was assumed in their investigation to be “sub-limit” braking. A large proportion of the accidents that involved over-braking also involved an emergency steering action. In general, PTW ABS does not allow the PTW to maintain stability while braking heavily in a curve/swove. This was reflected in the ABS model used in this study, which was not capable of maintaining stability in a swove when braking was severe enough to activate the ABS. This was a predictive study that used computer simulation to predict how the outcome of real accidents involving PTWs without ABS would have been changed if those vehicles had been fitted with ABS. This approach would result in evidence that has a high burden of proof according to the methodology defined earlier in this paper. However, the assumption that ABS would have no influence in any accident where braking occurred without loss of control contradicts several other studies – which suggests that ABS gives the rider more confidence and, in turn, results in higher maximum achievable deceleration. Therefore, the method used in the analysis may tend to underestimate the benefits.

Because of the limitations with both studies (i.e. Vavryn and Winkelbauer and Gwehenberger et al.), it was not clear which effectiveness was most appropriate, and therefore a weighted average from these two studies has been used for the best estimate. Based on the mid-range value from Kebschull and Zellner of 2% and a quality rating of 3 for each study, the best estimate is 6%. This was generated by multiplying the effectiveness by the score (2% x 3 and 10% x 3), summing (6 + 30) and dividing by the sum of the effectiveness scores (36 / 6). The extreme values from the two studies have been used to generate the overall range of effectiveness.

Using the 6% value for all accidents, and the best estimates of 18% for fatalities and 10% for serious casualties, a best-estimate effectiveness of 4.2% was calculated for slight casualties. The upper and lower effectiveness values are calculated using the same method. Table 5 shows the estimated benefit of fitting ABS. The figures for target population and effectiveness are shown in the table to allow readers to understand how the benefits have been derived. A best estimate of the effectiveness is also shown in the table, accompanied by minimum and maximum effectiveness values.
An increase in the number of safety measures, and the rate at which they are coming to market, can put an increased burden on the regulatory process. Impact assessments are, therefore, often required before there is sufficient voluntary market penetration to effectively measure the impact on the number and severity of road casualties using a retrospective statistical approach. Literature exists that describes the different types of research methods available – Elvik and Vaa (2004) – or to provide guidelines for assessing benefits – Burgett et al. (2008). However, within the budgets and timescales available it is often not possible to follow such guidance. TRL has seen an increase in requests for the assessment of the benefits associated with safety measures based on existing literature, rather than on new research. These are often required in short timeframes and on low budgets, thus limiting the depth of analysis that can be undertaken. This type of study has frequently identified widely varying and conflicting results amongst the existing literature, meaning that if scientific rigour is applied only wide ranges of potential benefits can be produced, which do little to resolve policy debate about the merits of proposals. It also allows stakeholders to select different values from within the quoted range, based upon broad assumptions that may or may not be accurate.

The project to develop a methodology to assess the benefits of advanced safety systems for PTWs provided an opportunity to begin to highlight these previous experiences and to consider the wider issues within a more formalised framework for undertaking cost–benefit analyses. Although the application of the methodology was limited to reviewing existing literature and accident data, the methodology itself was developed to include all benefit-assessment methods, in order to assist in identifying the limitations of existing estimates and also to help identify knowledge gaps.

### DISCUSSION

An increase in the number of safety measures, and the rate at which they are coming to market, can put an increased burden on the regulatory process. Impact assessments are, therefore, often required before there is sufficient voluntary market penetration to effectively measure the impact on the number and severity of road casualties using a retrospective statistical approach. Literature exists that describes the different types of research methods available – Elvik and Vaa (2004) – or to provide guidelines for assessing benefits – Burgett et al. (2008). However, within the budgets and timescales available it is often not possible to follow such guidance. TRL has seen an increase in requests for the assessment of the benefits associated with safety measures based on existing literature, rather than on new research. These are often required in short timeframes and on low budgets, thus limiting the depth of analysis that can be undertaken. This type of study has frequently identified widely varying and conflicting results amongst the existing literature, meaning that if scientific rigour is applied only wide ranges of potential benefits can be produced, which do little to resolve policy debate about the merits of proposals. It also allows stakeholders to select different values from within the quoted range, based upon broad assumptions that may or may not be accurate.

The application of the methodology to the estimation of the potential benefits of fitting ABS to PTWs highlighted many of these issues. An estimate was possible, but produced a large range of potential benefits because the quality of the estimate was severely limited by the ability to extract appropriate information from the existing literature. Some of the issues identified during the application of the methodology were:

- Variation in the presentation of the data within the studies. It was not always possible to relate the target population or effectiveness to an overall number of accidents/casualties so that they could be applied to the UK accident data.
- Not all assumptions were clearly stated, and widely differing assumptions were obviously used in different studies.
- Conflicting results from low effectiveness/high cost to high effectiveness/low cost.
- Insufficient detail on context and exposure. For example, papers where an effectiveness was stated for all casualties but no data were presented about the severity distribution of all casualties, so that different severity contributions in different countries could not be accounted for.

Many of the studies that were identified by Smith et al. (2008) had used appropriate methods to assess benefits. However, there was insufficient information available to directly apply the findings to an alternative source of accident data, i.e. it was not possible to trace the benefit estimate back to the original source data. Following the methodology described in this paper should lead to a consistent style in which benefit assessments are reported, which in turn will allow wider application of the results in different countries or under different regulatory options.

The methodology that has been developed is appropriate to meet the objectives of the specific research project for which it was intended. However, it could be considered just a starting point for a wider debate about how the scientific community and policy makers could work together to improve the quality, consistency and understanding of casualty-benefit assessment. Ideally, this would enable more effective implementation of the safety improvements that today’s rapid development of advanced active safety systems make possible.

### Table 5: Estimated benefit of fitting ABS to all PTWs

<table>
<thead>
<tr>
<th>Severity</th>
<th>Target population (all PTW casualties)</th>
<th>Effectiveness (%)</th>
<th>Estimated benefit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fatal</td>
<td>585</td>
<td>18 (9–36)</td>
<td>105 (52–209)</td>
</tr>
<tr>
<td>Serious</td>
<td>5991</td>
<td>10* (3–17)</td>
<td>599 (180–1018)</td>
</tr>
<tr>
<td>Slight</td>
<td>17 293</td>
<td>4 (0–7)</td>
<td>692 (0–1159)</td>
</tr>
<tr>
<td>Total</td>
<td>23 869</td>
<td>6 (1–10)</td>
<td>1432 (239–2387)</td>
</tr>
</tbody>
</table>

* This is the mid-point of the range (rounded to the nearest integer) and not a best estimate.

Note: Data in parentheses indicate minimum and maximum effectiveness values.
Future developments could include:

- Extending the methodology to include assessment based on regional representation, analytical quality and sample size

- More detailed guidance on specific analytical techniques (e.g. highlighting known confounding factors that should be accounted for in retrospective statistical studies, or the strengths and weaknesses of different ways of accounting for exposure)

- Development of new, improved data sources specifically designed to overcome limitations of existing data with respect to active safety systems

- Ways of encouraging widespread use of a common methodology

- Methods to ensure that the use of a common approach does not compromise the flexibility needed to assess a wide variety of different systems

- A methodology for assessing costs

CONCLUSIONS

- There are a range of methods that can be used to estimate the benefits of safety measures. None are perfect, and each has strengths and weaknesses. However, to the reader the limitations and assumptions are not always apparent. This can mean conflicting results, extended policy debate and slower implementation of technology.

- A generic methodology has been developed for a specific type of analysis that will assist both researchers and policy makers in identifying the most appropriate methods to use and the limitations of each method without unduly limiting the range of analysis that could be undertaken.

- This methodology has the potential to be expanded to the full range of casualty-benefit analyses, which, if successfully implemented in a wide range of research projects, could substantially improve the overall quality and cost-effectiveness of the research and the regulatory processes of implementing new technologies.

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This paper was published at the Driver Behaviour and Training Conference held in Amsterdam in November 2009. It provides a summary of the progress that has been made since the start of TRL's truck driving simulator project in 2003. The project has been funded, since its inception, by the Department for Transport and, since 2008, through the commercial vehicle driver training programme run for Allied Bakeries.

**Dr Nick Reed** is a TRL Academy Fellow and Senior Human Factors Researcher in the Human Factors and Simulation Group at TRL. Nick has been at TRL for more than five years following post-doctoral work in cognitive psychology and, in that time, has led numerous research studies using TRL’s car and truck driving simulator facilities. Nick’s work gained widespread coverage in the news with a simulator study investigating the effects of texting while driving. News items covering his study included television stories for BBC, Sky and CNN. He has also investigated the effect of energy drinks on driver fatigue and the distraction effect of roadside video billboard adverts. Nick has also been heavily involved, as a Lead Researcher, in TRL’s truck driving simulator projects researching the use of truck simulators for driver training. He has made significant progress in the analysis of driver performance and the provision of objective feedback to the driver. This work has enhanced the potential usefulness of simulation for driver training.

**Stephanie Cynk** has been at TRL for one year, following graduation with a degree in psychology. Since joining TRL, she has become involved in a wide range of topics within the Human Factors and Simulation Group. Her research has included examining the behaviour of powered two-wheeler riders and the legislation governing working hours for commercial drivers across Europe. Stephanie has been involved in physical ergonomics trials for the Highways Agency (HA). This work has assessed postural risk and task efficiency. Stephanie has also conducted analyses of simulator data for a study examining drivers’ behaviour in response to the presence of HA’s traffic-officer service vehicles.

**Professor Andrew Parkes** is Chief Scientist for TRL’s Safety Division and has very broad experience in the domain of driver behaviour and traffic safety, including the management of international collaborative research projects. Interests throughout his research career have expanded from the psychology and ergonomics of accident causation, through to a much wider view of the efficiency, acceptability and safety of a range of transport telematics systems. Andrew has written widely on the topics of driver behaviour, traffic safety and intelligent transportation systems – including *Driving future vehicles*, published by Taylor and Francis in 1993. His work has influenced the design of many commercial in-vehicle systems, and the development of international standards and guidelines for human–machine interface evaluation. His current research initiatives are in the areas of: advanced audio and visual display concepts; virtual reality for driver training; and driver impairment due to ageing, fatigue, medications or drugs.
TRUCKSIM: A BRIEF HISTORY

In 2002, UK road haulage was considered to be undergoing a crisis of recruitment of new drivers, and the retention of existing ones jeopardised its commercial position. European Union (EU) directives on working time and training were expected to put pressure on transport operators to recruit more drivers and to increase their fleet sizes. The European Commission Directive on Training for Professional Drivers (EU Commission, 2001), which was adopted in April 2003 (Directive 2003/59/EC), stipulates obligatory basic and continuous training for drivers of goods and passenger vehicles from September 2009. All drivers wishing to drive large goods vehicles (LGVs) in excess of 7.5 tonnes in a professional capacity will have to undergo training for, and obtain, a vocational certificate of professional competence (CPC), further to their LGV licence. Professional drivers will be required to undergo continuous training of 35 hours every five years to refresh their knowledge and skills. The directive offers scope for a proportion of this training to be conducted on a “top of the range” driving simulator.

On behalf of the Road Haulage Modernisation Fund (RHMF), the UK Department for Transport (DfT) established a research programme to determine the potential role of synthetic training in both initial licence acquisition and in skills development in experienced drivers. TRL commissioned the European Aeronautic Defence and Space Company (EADS) to produce an advanced full-motion-base truck simulator, and developed bespoke UK road databases and courseware. This system was christened “TruckSim”. The main objectives of the initial research programme were to expose a large number of students and freight companies to the potential of synthetic training and to inform DfT and RHMF of how synthetic training could be best integrated into training and testing programmes. Subsequent research focussed on fuel efficiency training.

1 TruckSim is the TRL truck driving simulator.
A simulated road network was created containing generic motorway, rural, urban and suburban areas with correct UK-specification junction layouts and signage, and a distribution centre for parking manoeuvres. Various features of the driving experience – including weather, ambient lighting, road friction and truck load – can be adjusted from the simulator control room. Exercises were created to examine drivers’ responses to the different elements of the simulated environment. Figure 3 shows a map of the road system used in the study.

The simulator display has a refresh rate of 60 Hz, a resolution of 1280×1024 pixels per channel and approximately 2.9 arc minutes per pixel. Figure 1 shows a line drawing of the simulator, and Figure 2 shows some of the internal and external features of the simulator.

The pod is mounted on a combination of hydraulic and electric actuators to give full motion with six degrees of freedom: pitch, roll, yaw, heave, surge and sway. An eight-speed manual gear box (four over four with range change) is provided in the cab. The motion parameters are further described in Table 1.

The truck simulator provides a “real” experience; it duplicates the operation of a vehicle and reproduces a world outside. Scenes are delivered with sufficient reality to ensure that the driver becomes truly immersed in the experience. Up to 40 other vehicles with intelligent behaviour can be displayed in the scene at any one time. Some example street scenes are shown in Figure 4.

Both internal and external information is accurately reproduced, thus ensuring that drivers feel as if they are sitting in the cab of their own vehicle. Quality audio (3D sound) and visual systems contribute to making the experience as real as possible.
Having implemented the simulator, the next step was to evaluate it in terms of its effectiveness as a training tool. The truck simulator training was evaluated using qualitative methods, investigating issues such as simulator sickness, similarity to driving a real truck, quality of simulation, handling realism and general acceptance.

A total of 616 professional truck drivers took part in the evaluation study. They participated in two Computer-Based Training (CBT) tasks, similar to theory tests that drivers must pass before licence acquisition. The first task asked 35 multiple-choice questions and the second was a hazard-perception task from a computer demonstration of truck driving. Next, trainees completed an exercise on a part-task simulator (a static version of the full-motion TruckSim) with guidance from a professional driver trainer to introduce them to the appearance and controls of a simulated environment.

Under the supervision of a professional trainer, each trainee completed three exercises in TruckSim. The first was a familiarisation drive on a motorway. The second and third exercises were selected from the choice of a poor-weather drive, an urban drive, a route including high-speed bends, and a reversing exercise. Questionnaires were distributed in order to obtain opinions of the exercises, and a further questionnaire assessed levels of simulation sickness, subjective evaluations of realism, and acceptance of the simulator as a training tool.

The truck simulator received a positive response from the truck drivers involved. Although the overall scores for similarity to driving, quality of simulation and handling realism were generally high, the simulator was reported as being particularly similar to real truck driving in terms of overall cab design, headlights and the mirrors. The aspects of simulation quality that received the most praise were the road layout, brightness, clarity of the display, and the overall driving environment. Handling realism received the most positive scores for signal turns and seeing the road and other road users.

The research programme also identified areas that needed to be addressed in order to improve TruckSim further as a training tool. The similarity of the steering and deceleration to driving a real truck was rated as low. In relation to the simulation quality, trainees regarded the traffic and realism of cyclists as poor. Finally, the realism of controlling in a turn and service braking received lower scores.

Simulator sickness was generally low. However, there was a large variation in the experience of simulator sickness, with a few participants experiencing high levels of sickness. High levels of simulator sickness correlated with lower ratings of simulator similarity, quality and handling realism. A further finding was that participants older than 30 years were more likely to experience higher levels of simulator sickness. The simulator may therefore be better suited to training younger drivers.
The exercises that were conducted affected drivers’ perceptions of TruckSim. Those who experienced the poor-weather exercise viewed it favourably and had more positive perceptions of the similarity to driving, quality and realism of the simulator. The reversing exercise was less favoured, and had the opposite effect on perceptions of the similarity to driving, quality and realism of the simulator.

Of particular importance to the research, the majority of drivers did not feel that training in the simulated environment affected their learning in their normal cab. The trainer was also deemed influential in their learning experience.

**FUEL EFFICIENCY**

The TruckSim evaluation phase demonstrated that drivers had a subjective preference for exercises involving continuous driving rather than slow-speed manoeuvres. Fuel efficiency was therefore an obvious target for simulator training scenarios, particularly since fuel consumption is a directly measurable property of every drive completed. It is therefore easy to compare performance between drives/drivers – unlike accident risk, the level of which is harder to capture in a short, naturalistic drive. DfT commissioned TRL to undertake a further study using TruckSim in order to develop the simulator training capability and to gain further feedback from an additional group of drivers.

Performance in the simulator scenarios was assessed on the critical measures used in the Safe And Fuel Efficient Driving (SAFED) standard (DfT, 2003): fuel used, gear changes and time taken. The SAFED training programme uses a real vehicle and requires drivers to complete on a route lasting one hour. Drivers are then given some classroom training on safety and fuel efficiency before they complete the same one-hour route again. Results demonstrated that drivers typically reduce fuel consumption by 2–12% and make fewer gear changes, but do not take any longer to complete their journey (DfT, 2005).

After a familiarisation drive in order to become acquainted with the controls of the simulator and the feel of driving in the virtual environment, participants in the TruckSim programme were required to complete two drives on the same route. Each simulator drive lasted between 15 and 20 minutes and encompassed rural, urban and high-speed driving sections. Between the two drives, participants were given training in fuel efficiency by a qualified truck driver trainer. A total of 394 professional truck drivers participated in the programme, and their performance in each of the key measures was recorded. On average, drivers made 12.5% fewer gear changes, used 3.33% less fuel and took 6.59% less time to complete the route. These differences are comparable to those observed in on-road SAFED training. However, these improvements may have been an artefact of better simulator driving rather than better truck driving. Therefore, a study was undertaken to demonstrate that skills learned in the simulator would transfer to behind-the-wheel driving techniques.

**TRANSFER OF TRAINING**

This next phase of the work was again funded by DfT. TRL recruited 60 truck drivers to experience fuel efficiency training in TruckSim on three separate occasions over a period of six months. The drivers came from 11 different companies that operated in a variety of industries, including automotive, food, and hazardous chemicals. To investigate real-world driving, the fuel efficiency of the participating drivers was monitored for a working week before and after each of their three visits to TRL. This meant that their on-road performance could be tracked in relation to their training in the simulator. For comparison and control, the fuel efficiency of an additional 60 drivers with similar profiles to those undergoing simulator training, and from the same company, were monitored. Finally, none of the drivers participating in the study received any other driver training for the duration of the project.

The simulator experience received by drivers coming to TRL consisted of a short period of familiarisation before a first attempt at driving a mixed rural and urban route, observed by a fully qualified driver trainer. Having completed the exercise, the trainer gave drivers instruction on how to improve their driving style in order to complete the route with greater fuel efficiency. Each driver then had a second attempt at the exercise, giving an opportunity to demonstrate improved fuel efficiency. For all exercises, the drivers operated a simulated version of the Mercedes Actros 2544 articulated (6×2 axle configuration) lorry unit with 100% load (estimated gross vehicle weight 44 tonnes).

In a further development of the training package, an analysis tool was developed in order to evaluate performance in the two exercises automatically. The simulator recorded data about various aspects of each drive at a rate of 60 Hz. These data included information about the actions of the driver (e.g. steering angle, accelerator/brake/clutch depression); the behaviour of the vehicle (e.g. speed, lateral/longitudinal/rotational acceleration); the behaviour of the vehicle in the context of the external environment (e.g. distance to vehicle in front, lateral position); and the simulated engine and transmission characteristics (e.g. fuel used, revolutions per minute – rpm – and engine torque). Using the data of drives completed in the previous projects and correlating these measures against fuel efficiency, it was possible to determine benchmark values for good and bad fuel-efficient driving practices. The analysis tool then scored drivers on a variety of criteria to give an indication as to how well they drove the vehicle in terms of fuel efficiency. A grade was given for each aspect: green for good, yellow for fair and red for poor fuel-efficient driving behaviour. The instructor could then provide tailored feedback to the driver as to the aspects of their simulated and real-world driving on which they should concentrate in order to make the biggest improvements.

Results in the simulator showed that drivers made an 11% improvement in their fuel efficiency over the three visits to the simulator, with the biggest gain being made during the first visit. It was also clear that drivers retained what they had learned from one visit to another, as fuel efficiency did not
deteriorate between visits. The simulator data revealed that drivers were handling the vehicle in a much more efficient manner. Average rpm observed during periods of acceleration dropped by 22%, resulting in the engine operating in a more efficient region and generating 45% higher torque. There were also 29% fewer gear changes over the course of the drives. It would be easy to assume that drivers simply slowed down in order to achieve these improvements, but the data show that drivers were actually around 8% faster overall.

The key question, then, was: would this behaviour be transferred to the drivers’ real-world driving back in their everyday work? It was found that relative to the control group, the simulator-trained drivers showed a progressive improvement in their fuel efficiency, returning a 16% improvement in miles per gallon (mpg) after the third training session.

Note that this improvement was greater than that achieved in the simulator. It was also higher than the improvement reported by Strayer and Drews (2003), who found that drivers trained in a simulator showed an average improvement of 2.8% in fuel efficiency for the six-month period following training. It was concluded – see Parkes and Reed (2005) – that skills learned in TruckSim had indeed transferred to behind-the-wheel behaviour, providing the basis for a commercial-driver fuel efficiency training package.

ALLIED BAKERIES

The first company in the UK to use TruckSim to provide training for their truck drivers on a commercial basis was Allied Bakeries (AB). This commenced with a pilot study, supported by the Welsh Assembly Government, in which AB committed six drivers to a simulator training programme. The study design was similar to that described by Parkes and Reed (2005), who examined the transfer of fuel-efficient driving from the simulator to the road. However, in the study described in this paper drivers visited TRL for training on two occasions rather than the three used in the study by Parkes and Reed. AB was able to keep detailed fuel consumption records for the six drivers involved in the study, and to minimise other factors that may have affected fuel efficiency. For example, AB ensured that each driver always drove the same vehicle and always drove on the same routes throughout the period of study. The drivers were chosen to represent a range of driving styles, and to cover different normal driving environments.

Training was provided by an Approved Driving Instructor (ADI) for all forms of commercial vehicle. Participants visited TRL for two training sessions. In addition to this, all participants visited TRL for a familiarisation visit in order to see the simulator facility and to have a brief drive of TruckSim to help reduce any feelings of anxiety that they might have about training on the simulator at TRL. This familiarisation visit was conducted on 10 April 2008. The first training visit was conducted in July 2008; the second in September 2008.

Drivers were asked to operate a simulated Mercedes Actros 2541 rigid (6×4 axle configuration) lorry unit with 50% load (estimated gross vehicle weight 17 tonnes). This vehicle type was selected in order to be most similar to the type of truck and load typically driven by the AB drivers. The training route was a mixture of rural and urban driving, with a number of events designed to challenge the driver and provide opportunities to display fuel-efficient driving practices. Drivers received feedback on their performance using a revised version of the automated assessment system, tailored to suit the type of simulated vehicle driven in this training programme.

A potential problem that may affect all training providers was difficulty in scheduling drivers for training sessions. Training on the simulator required coordination of trainees, in order for them all to attend the facility on the specified dates. Issues such as illness, injury, departure and annual leave all affected driver bookings for the training programme. However, on completion of the training programme results demonstrated that trainees produced a 25.6% improvement in simulated fuel efficiency. Exploration of the changes in behaviour indicated that this was accompanied by a reduction in rpm (reduced by 33.4%) resulting in greater engine torque (increased by 50.5%) when accelerating and a reduction in fuel wastage when slowing the vehicle. Drivers also made significantly fewer gear changes in the simulator after training (down by 26.4%). This also contributed to greater torque values and better vehicle sympathy, but may have been owing partially to increased familiarity with the simulator gearbox.

Figure 5: Mean percentage improvement in on-road fuel efficiency
Results in the real world showed that simulator training was associated with a mean fuel efficiency improvement of 7.3%. The biggest improvements were seen for drivers who completed mixed driving routes, whereas the smallest improvements were seen for those who usually drove in the urban environment. When the observed real-world fuel efficiency improvements were applied to annual fuel usage the cost benefits were considerable, and CO₂ emissions would be reduced by over 250 tonnes per year. Based on that assumption, the improved fuel efficiency of the trained drivers would provide a return on investment in a little over four months.

This study supported the results of the previous simulator fuel efficiency training programme conducted at TRL, demonstrating that simulator training can achieve significant and pragmatic fuel efficiency savings on a commercial basis.

Further training
Following the success of the pilot driver training programme, AB commissioned training of a further group of 32 drivers from its Cardiff depot, all of whom were to repeat the same training process as that completed by the drivers in the pilot study. Convinced by the success of the pilot programme, AB did not apply the restrictive constraints whereby trained drivers would keep to the same route and vehicle. Consequently, it is difficult to assess the success of this programme at the level of the individual driver. However, partway through the training programme AB has reported a steady improvement in the overall fuel efficiency of the fleet. The company has also observed a notable reduction in the number of accidents, and its drivers report feeling less stressed at the end of a shift and having a greater sense of esteem following training. However, these are anecdotal findings and should therefore be treated with due care. It is now also a year since on-road fuel efficiency data were first collected for the AB drivers involved in the original pilot. Only one driver has remained on the same route and with the same vehicle type throughout this period. His mean fuel efficiency improvement following training was 15%, and over the year this has gradually reduced to a sustained improvement of 7%. This would give AB a clear return on investment over the cost of the simulator training.

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A study in which the real-world fuel efficiency of cohorts of drivers trained in the simulator at different frequencies (every three months; every six months; annually) was continuously monitored (with an associated cost–benefit analysis) would establish the optimal training regime.

Discussion
The TruckSim facility at TRL has had a steady transformation from an initial curiosity to the basis of a genuine, cost-effective business opportunity to provide advanced training to professional truck drivers. The initial phases of the programme provided a strong foundation for the understanding of how TruckSim might best be used for training, and provided the data that would go on to be used in creating the benchmarks for the automated driver assessment system. In the second phase of TruckSim, a shift in thinking led to significant advances in training methodology and simulator use. As a matter of course, a simulator generates vast quantities of data about the driving situation: pedal depression, steering angle, gear usage, vehicle speed, vehicle position, engine speed, engine torque, and so on. While the simulator can be used as a proxy for on-road training, these data provides a rich source of information that can be used to understand a driver’s capabilities and training needs. Failing to exploit that information amounts to neglecting a key area in which the simulator has a highly significant and functional benefit over the use of real trucks for training.

Furthermore, it was observed that the use of simulator data to diagnose driver faults appeared to produce a marked change in the dynamic between trainer and trainee. Instead of a trainer delivering drivers with subjective criticism of their performance (which may have been met with suspicion or even disdain), the simulator provided objective and impartial feedback on driver performance. The trainer is therefore able to focus on helping a driver to correct the areas of substandard performance. Removing this element of subjectivity seems to have improved engagement by trainees in the training process and generated more positive outcomes as a result.

The transfer of fuel efficiency benefits trained in the simulator to real-world driving has shown that simulator training can cause genuine improvements in real-world driving performance. The growing emphasis on Corporate Social Responsibility (CSR) requires companies to demonstrate that they are taking reasonable steps to operate ethically and sustainably. The fuel efficiency improvements that have been observed following simulator training are associated with reductions in engine emissions, thereby assisting companies in meeting their CSR objectives.

The EU Driver Training Directive 2003/59/EC (EU Commission, 2003) makes it compulsory for drivers of lorries, buses, coaches and minibuses (when being used for hire and reward) to hold not only a driving licence but also a CPC for drivers. The legislation requires existing drivers to undertake 35 hours’ periodic training over a period of five years (from 10 September 2008 for drivers of passenger-carrying vehicles, and from 10 September 2009 for drivers of LGVs). Training sessions must be in periods of not less than seven hours. Fulfilling this requirement allows a driver to receive the CPC. The directive permits a proportion of the driver training for the CPC to be completed on a “top-of-the-range simulator”. Subject to certification by the relevant authority (in the UK, this is the Joint Approvals Unit for Periodic Training), training courses provided on TruckSim may form an appealing component of the CPC training process.

To conclude, the UK’s first full mission, high-fidelity truck simulator, TruckSim, has matured from an initial novelty into an effective training tool that can deliver cost-effective driver training. The simulator training process has been gradually refined, and the development of automated driver assessment software to support the simulation has been fundamental in the success of the simulator training programme. TruckSim has carved itself a niche for professional driver training. The extent to which this niche shall develop remains to be seen.
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The following pages list all TRL reports published in 2009. We also list all papers accepted for publication in journals and papers presented at conferences during 2009 as well as books, book chapters, web publications and significant press and magazine articles. TRL’s Library and Information Centre also produces a range of review publications for our customers, called “Current Topics in Transport”. Those added during 2009 are also listed. An index of TRL authors is included for ease of reference. (It should be noted that in the citations, any name marked with an asterisk denotes an author from another establishment with whom we have collaborated on the work.)

During 2009, we introduced a new report series, called “Insight Reports”. This report series is now TRL’s premier publication series. Each Insight Report is written by a senior TRL scientist, featuring their specialist topic area. Insight Reports will often consolidate the experience gained over many projects, and distil and illustrate the key concepts of that topic or demonstrate innovative thinking in an emerging area.

Copies of any of the publications listed can be obtained through our Library and Information Centre. Contact details are provided on p 129.
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The TRL Annual Research Review 2009 presents a summary of the year’s activities and achievements. It includes an overview of TRL’s main research highlights, a description of some of the specialist services and consultancy support that TRL provides for its customers and a comprehensive listing of reports and papers published in 2009. Some selected full papers are also included as follows:

- Developing the automatic measurement of surface condition on local roads. Alex Wright, Helen Viner, Andrew Gallagher and Edward Bunting.

- Car rollover mechanisms and injury outcome. Richard Cuerden, Rebecca Cookson and David Richards.

- Quantifying the benefits of new bus priority logic in SCOOT. Helen Gibson.

- A common approach to understanding strengths and limitations of different cost–benefit analysis techniques. Tanya Robinson (née Smith) and Iain Knight.

- From research to commercial fuel efficiency training for truck drivers using TruckSim. Nick Reed, Stephanie Cynk and Andrew Parkes.