TRL Limited

PUBLISHED PROJECT REPORT PPR066

PAVEMENT WEAR FACTORS

Version: 1

by V M Atkinson, D Merrill and N Thom

Prepared for: **Highways Agency**
(Mr W Lloyd)

	Approvals
Project Manager	V M Atkinson
Quality Reviewed	W H Newton

This report has been produced by TRL Limited, under/as part of a Contract placed by Highways Agency. Any views expressed are not necessarily those of Highways Agency.

CONTENTS

Executive summary

Heavy vehicle traffic loading is a key determinant of pavement structural wear and therefore needs to be considered in pavement structural design. In the UK, pavement structural design takes into account the expected traffic flow, growth in traffic over the life of the pavement, distribution of traffic between lanes and vehicle wear factors. The UK's standard method for estimating traffic loading for pavement design is set out in Section 7.2.1 of the Design Manual of Roads and Bridges (HD24).

This report summarises a project for Highways Agency which reviewed the 1996 version of HD24. The objects of the project were to:

- examine the effects of heavy vehicles on pavements in the UK
- propose a robust method that will enable this effect to be taken into account in a pavement design procedure
- produce a draft for an updated version of HD24.

The report describes the development of UK wear factors leading to HD24/96. It then considers more recent research and non UK methods of incorporating traffic loading into pavement design, before considering which factors should be taken into account in the revised method.

The recommended changes to HD24/96 included revising the:

- Vehicle classification system to reflect changes in the goods vehicle fleet and to harmonise it with other sections of the Design Manual for Roads and Bridges. The 3 and 4-axle articulated vehicles classes would be amalgamated and a separate 6-axle articulated class created.
- Growth factors, using the 1997 National Road Traffic Forecasts.
- Method of calculating the distribution of commercial vehicle traffic between lanes. The lane distribution on two, three and four lane carriageways was assessed and it was concluded that a single distribution curve should be used. In addition, it was recommended that the percentage of commercial traffic in the heaviest traffic lane should be calculated (rather than the percentage in lane 1) because factors such as junction design can result in the majority of commercial traffic travelling in lanes other than lane 1.
- Vehicle wear factors using data from Weigh-In-Motion (WIM) sites. It was recommended that appropriate dynamic and safety factors should be applied to the WIM data. Revised vehicle wear factors were proposed.

These recommendations were incorporated in the 2006 revision of HD24.

Whilst the project concentrated on structural wear effects, some of the factors considered also affect the serviceability of the pavement (such as surface skid resistance, rutting, cracking and roughness). The report recommends that the factors influencing serviceability wear should be examined in greater detail.

1 Introduction

The objective of pavement structural design is to choose appropriate materials of appropriate thicknesses to ensure that the pavement can carry traffic over the defined design period and meet the requirements of the assumed structural maintenance regime. Although many factors can be taken into account in pavement structural design, vehicle traffic has traditionally been the key determinant. The UK's standard method for estimating traffic loading for the design of road pavements is set out in Section 7.2.1 of the Design Manual of Roads and Bridges (HD24).

This report summarises a research project for the Highways Agency which reviewed the 1996 version of HD24. The objectives were to:

- examine the effects of heavy vehicles on pavements in the UK
- propose a robust method that will enable this effect to be taken into account in a pavement design procedure
- produce a draft for an updated version of HD24.

This report reviews generic methods of relating pavement deterioration to vehicle loading (Section 2), the development of UK wear factors (Section 3), recent research on wear factors (Section 4) and non UK methods of incorporating traffic loading into pavement design (Section 5). It then considers various factors which might be included in a revised methodology (Sections 6 and 7) and recommends revisions to HD24 (Section 8). These recommendations were incorporated in the 2006 revision of HD24. The report also contains information about calculation of the revised vehicle wear factors (Section 9 and Appendix B).

2 Generic Methods of relating pavement deterioration to vehicle loading

There are a variety of methods of taking vehicle loading into account when designing a road. These vary from very detailed approaches, where many traffic and pavement variables are considered, to very simple approaches based on broad traffic spectrums. Three levels of increasing complexity are outlined in this Section: Traffic Classes, Load Equivalence and Discrete Damage Analysis.

2.1 Traffic Classes

A simple method is to have different standard designs based on different classes of traffic / road. For example:

- lightly trafficked roads (e.g. housing estates and country lanes)
- moderately trafficked roads (e.g. link roads)
- trunk roads and motorways (often long life pavements).

The classes could be based on any agreed measure of the traffic, such as the type of road or the flow of heavy goods vehicles.

These methods do not necessarily rely upon a clearly stated relationship between pavement wear and traffic. Instead the result will be a limited set of pavement designs that are appropriate for the stated traffic. This would lead to step changes in pavement thickness for different classes of traffic / road, with different thicknesses for traffic levels just below or just above the threshold level.

2.2 Load Equivalence

In the load equivalence method the traffic predicted during the pavement's design life is converted into an equivalent number of ‘standard’ axles. The pavement materials and thickness of construction layers are then taken from design charts.

Since the AASHTO road test (Highway Research Board, 1962), the method of load equivalence has been widely adopted. (The current UK method of computing design traffic uses the Load Equivalence approach.) Each class of vehicle is assigned a vehicle wear factor to convert its loading into a number of equivalent ‘standard’ axles, which would apply the same loading to the pavement.

Vehicle wear factors can be based purely upon the load applied by each axle, or can be modified to take account of other vehicle parameters, such as:

- axle spacing
- wheel type
- suspension.

Load equivalence is a tried and tested method which allows analytical design and can accommodate changes to materials and vehicles.

2.3 Discrete Damage Analysis

Discrete damage analysis methods look at the pavement / vehicle interaction. They attempt to model, as closely as is reasonably possible, the response of a pavement (and resulting wear) under every single wheel load. The response of the pavement, in terms of the stresses and strains induced by wheel loads, will vary according to both the loading applied and the way in which the pavement distributes those loads. The loading depends upon vehicle factors such as;

- wheel load
- wheel type

- tyre pressure
- axle spacing
- dynamic loading (related to vehicle suspension and pavement roughness)
- vehicle speed.

To calculate the response of the pavement it is necessary to know not only the thickness of the pavement materials but also the way in which these materials react to temperature and loading time.

The response of the pavement under each vehicle is predicted and used to estimate the wear caused by that vehicle. Using a wear relationship such as Miner's hypothesis and the spectrum of traffic that the pavement will be carrying, the estimated wear attributable to each vehicle is accumulated. This continues with the pavement being modelled throughout its required design life. If the failure criteria are not reached then the pavement design is satisfactory, otherwise the pavement design will need to be altered and the analysis re-run until a satisfactory solution is reached.

While discrete damage analysis has the potential to accurately model vehicle / pavement interaction it relies on having accurate predictions of factors such as temperature and vehicle speed, and on accurately defining pavement deterioration in terms of pavement response.

2.4 Discussion

The adoption of a limited number of traffic classes would mean that all pavements within one class would have to be designed for the maximum amount of traffic in that class (to avoid knowingly under-designing some pavements).

There are many variables that affect pavement life. These include the traffic composition and speed, the construction materials, the foundation on which the pavement is built, the climate and the reaction of the pavement materials to variations in climate. The discrete damage analysis approach involves predicting the behaviour of many different factors over the design life of the pavement.

A compromise which allows an analytical approach to be taken without becoming unworkably complicated is the load equivalence method. This is the current method used in the UK and has been proven to work although it does not take into account all the variables. For example, no account is taken of the performance of asphalt materials in different temperatures.

Of these three methods, the load equivalence method is considered to be the most robust and workable. However, it is necessary to build in some conservatism to allow for the influence of factors which are not taken into account.

3 Historical development of UK wear factors

Early methods of pavement design were based on the number of commercial vehicles expected to use the road. However, by the 1950s it was appreciated that the wearing effect of commercial vehicles increases rapidly with increasing axle load and that road design would have to take into account the axle load spectrum of traffic predicted to use the road.

In the early 1950s, portable weighing platforms were used in an initial attempt to characterise the axle load spectrum of commercial traffic. The UK's first experimental dynamic weighbridge (measuring wheel loads of vehicles travelling at normal highway speeds) was introduced in 1958 and an improved design became available in 1963 (Trott & Grainger, 1968). As the weighbridges only measured nearside wheel loads, axle loads were estimated by doubling the measured wheel load. These axle loads were then segregated into 10 load bands and the frequency of axles in each band was reported. The weighbridges did not include any system of vehicle classification (for example, into rigid or articulated vehicles).

Meanwhile, the AASHTO Road Test (Highways Research Board, 1962) enabled pavement wear to be related to axle loads. It showed that, for both flexible and concrete pavements, the wearing effect of axles was approximately proportional to the fourth power of the axle load (the 4^{th} power law). Using this relationship the measured axle-load spectrum could be expressed in terms of an equivalent number of 'standard' axles.

When Road Note 29 ('A guide to the structural design of pavements for new roads') was revised in 1970 (Road Research Laboratory, 1970), the AASHO wear factors were used to relate pavement thickness requirements to the number of 'standard' axles that the pavement was designed to carry. The design curves presented in Road Note 29 were derived from the observed performance of experimental roads in which weighbridges were installed.

The only information generally available when designing new roads was the estimated initial traffic flow and the likely growth rate. To use the design curves in Road Note 29, it was necessary to convert this information into the cumulative number of 'standard' axles which would pass over lane 1 (the lane which would see the heaviest traffic) during the design life of the road. Thus it was necessary to derive typical axle-load spectra for various types of road, the average number of 'standard' axles for the commercial vehicles on those roads, and the distribution of commercial vehicles between lanes.

Between 1966 and 1973, visual counts of traffic were carried out at 20 sites covering a wide variety of roads ranging from motorways to local residential streets (Currer, 1974). Information was collected on both the total number of vehicles and the proportion of commercial vehicles. Where more than one lane was present, a breakdown of traffic was given for the near side lane and either the overtaking lane (two lane roads) or the centre lane (three lane roads). The vehicle count segregated commercial vehicles into a number of categories according to the type of vehicle (rigid, articulated, etc), the axle configuration and the number of wheels on each axle.

Currer considered that the vehicle classifications for structural pavement design could be simplified into:

- 2-axle rigid
- 3-axle rigid
- 4-axle rigid
- 3-axle articulated
- 4-axle articulated
- 5 or more axle, articulated.

Currer combined information from the TRL weighbridges with that from the traffic surveys to produce axle load distributions for each of the above vehicle classifications. The load on each axle in kN (L) was then converted into the number of equivalent 80kN ‘standard’ axles, using the relationship:

$$\left(\frac{L}{80}\right)^{\gamma}$$

Where:
γ = exponent (found to have a value 4 in the AASHO experiments).

Using the measured proportion of vehicle types and the estimated number of ‘standard’ axles for each vehicle type it was possible to calculate the average number of ‘standard’ axles per commercial vehicle. This number, known as the wear factor, was found to be dependent on the type of road. It ranged from 1.08 for heavily trafficked motorways and trunk roads (carrying over 1,000 commercial vehicles per day in each direction) to 0.45 for roads carrying less than 250 commercial vehicles per day in each direction.

By 1979 there were 31 weighbridges at 15 locations and far more comprehensive data were available on the magnitude of wheel loads. There had also been significant changes in freight transport, with more multi-axle vehicles, a higher proportion of fully loaded vehicles and some types of vehicle covering larger annual mileage. Information on traffic flows and axle loads was analysed to bring the estimates of wear factor and lane distribution up to date (Currer and O'Conner, 1979).

Between 1970 and 1977 the weights of commercial vehicles on motorways had increased. This resulted in increases in the wear factors of approximately 70% in the near-side lane and 80% in the centre lane. Similar trends were observed at the trunk road sites, except where the opening of a motorway resulted in a drastic reduction in the number of commercial vehicles using the road. The increase in the wear factor was mostly due to a decrease in the number of lighter commercial vehicles (2 and 3-axle rigid and 3-axle articulated) and an increase in the number of heavier commercial vehicles (4-axle rigid, and 4 and 5-axle articulated).

To provide the necessary inputs to pavement design, it was assumed that the number of axles per commercial vehicle would continue to rise over the next 30 years (Currer and O'Conner, 1979). Future axle wear factors for four different categories of road were calculated by estimating loading conditions for the each vehicle classification and extrapolating from historic data. Wear factors were calculated by multiplying the axle wear factor by the number of axles per commercial vehicle. It was assumed that both the amount of commercial traffic and the amount of wear for each commercial vehicle would increase over the design life of a pavement. The average vehicle wear factors (number of ‘standard’ axles per commercial vehicle) varied from 2.9 on the most heavily trafficked roads (> 2,000 commercial vehicles per day) to 0.75 on the lightly trafficked roads (< 250 commercial vehicles per day).

In 1988, data from the weighbridges were re-analysed, incorporating data collected between 1978 and 1987 (Robinson, 1988). Robinson compared the wear factors predicted by Currer and O'Conner with those calculated from weighbridge data. There was an increasing discrepancy, with the wear factors calculated from the weighbridge data being significantly lower than the predicted values.

Robinson also examined data on goods vehicle axle weights from roadside surveys (the axles were weighed while the vehicles were either stationary or moving very slowly). Robinson concluded that vehicle wear factors derived from static axle weights should be converted to equivalent weighbridge values by multiplying by 1.3.

The use of data from static weighing surveys enabled vehicle wear factors to be calculated separately for each class of vehicle. These wear factors were presented in paragraph 3.14 of Volume 7 Section 2 Part 1 HD 24/96 of the Design Manual for Roads and Bridges (see Table 3.1).

Table 3.1 : Vehicle Wear factors (from HD 24/96)

Vehicle type	Wear factors
Buses & Coaches	1.30
2-axle rigid	0.34
3-axle rigid	1.70
3-axle articulated	0.65
4-axle rigid	3.00
4-axle articulated	2.60
5+-axle articulated	3.50

Based on past trends in vehicle wear factors and likely future changes, Robinson developed a simple equation to predict future wear factors and to calculate historic wear factors:

$$D2 = D1 \times \frac{\left(0.91^{T1} + 0.42\right)}{\left(0.91^{T2} + 0.42\right)}$$

Where:

D2 is the wear factor for a given past or future year
D1 is the wear factor for a given base year
T1 is the number of years from 1960 to the given base year
T2 is the number of years from 1960 to the given past or future year

Robinson considered that by 2005 average vehicle wear factors of commercial traffic would be likely to be 1 to 1.5 times the 1988 values.

HD 24/96 contained two methods of calculating design traffic from traffic flows: a standard method and a detailed method. The standard method was designed for use on new pavement schemes or schemes where there is uncertainty about the traffic whereas the detailed method was designed for use on maintenance schemes where the current traffic composition is known.

The standard method used one of four charts covering single and dual carriageways for design periods of either 20 or 40 years. The design traffic was defined according to the daily flow of commercial vehicles and the proportion of the OGV2 class of commercial vehicles. The standard method was a conservative approach that covered the risk of under-designing the pavement as there is inevitably considerable uncertainty in predictions of future traffic.

The detailed method was more explicit; the flow of vehicles in terms of at least two vehicle classes (OGV1 and OGV2) was required to calculate the design traffic. The basic equation for the detailed method was calculated for each vehicle class:

$$\mathrm{T} = 365.\mathrm{F.G.Y.W}.10^{6} \text{ msa}$$

$$\text{Design Traffic (msa)} = \mathrm{P} \times \mathrm{T}$$

Where T = Total flow in million 'standard' axles (msa)
Y = Design period (years)
F = Daily flow (vehicles)
G = Growth factor
P = Proportion of vehicles in the left hand lane
W = Vehicle Wear Factor

Both methods used vehicle wear factors to link the flow of vehicles to the design traffic. However, for the same input data (daily commercial vehicle flow and the proportion of OGV2 vehicles) the two methods produced different results; the primary reason being the need for additional conservatism where there is less certainty about the traffic which will use the pavement.

4 Recent research on wear factors

Since Robinson's work (which produced the wear factors used in HD 24/96), there have been further changes to the vehicle fleet and a large increase in commercial vehicle traffic. One of the most notable changes was the increasing number of 6-axle articulated vehicles. The vehicle wear factors produced in 1988 referred to '5 axles or more' as a single class, as the sample of 6-axle vehicles was small. At the same time, vehicle lading factors (goods moved as a proportion of maximum carrying capacity) of the heaviest vehicles tended to decline, reflecting changes in the commodities being carried.

Developments were also made in the measurements of axle loads, with the installation of newer weigh-in-motion (WIM) systems enabling large amounts of data to be gathered classified by vehicle type. The development of information processing has also made it possible to take into account more detailed vehicle / pavement interaction as a part of the design process.

Recent research has suggested that the vehicle wear factors in HD 24/96 no longer reflect the current vehicle fleet. Some of the most significant studies carried out in the UK over the past decade are summarised here.

4.1 Wear factors from static axle weights, WIM systems and Eisenmann equation

In 1997 TRL completed a project on heavy goods vehicles and road wear. A number of different methods of estimating vehicle wear factors were identified. These were:

- applying the 4^{th} power law to static axle weights from roadside surveys,
- applying the 4^{th} power law to static axle weights calculated using the CSRGT (Continuing Survey of Road Goods Traffic) multiplied by a static / dynamic adjustment factor,
- applying the 4^{th} power law to dynamic axle weights measured using WIM systems, and
- using the Eisenmann road stress factor equation (Eisenmann et al, 1986) – taking into account tyre type and pressure, dynamic effects (including suspension characteristics), load sharing between axles and axle configuration, as well as axle weight.

The Eisenmann road stress factor equation gives a wear factor for each axle, the vehicle wear factor being the sum of factors for each axle.

$$AWF = \left(1 + 6(DLC)^2 + 3(DLC)^4\right) \times (WC \times CP \times LE \times AC \times S)^4$$

Where:

AWF is the axle wear factor (dynamic component x static load).
DLC is the dynamic load coefficient (coefficient of variation of the ratio of dynamic to static load).
WC is the wheel configuration factor that varies for single, super-single and dual tyres.
CP is the tyre contact pressure factor, based on the manufacturer's recommended tyre pressure and split into three bands - within 15% of recommended pressure, 15% below recommend pressure or 15% above recommended pressure.
LE is the load equalisation factor calculated for each tandem and tri-axle group.
AC is the axle configuration factor that is calculated for single, tandem and tri-axles.
S is the weight of the axle.

Many of the elements in the Eisenmann equation were estimated.

TRL suggested average wear factors derived from this research (see Table 4.1). Although these were broadly similar to those used in HD 24/96, they were generally lower, in particular for 6-axle articulated vehicles.

4.2 Wear Factors from UK WIM sites

In 1998, Hakim and Thom investigated the use of data from WIM sites for calculating vehicle wear factors (Hakim and Thom, 1998). They also explored the effect of changing the power exponent. They found that:

- a lower power may be more appropriate for non-structural wear in asphalt and for fatigue cracking in asphalt
- a higher power may be appropriate for cracking in rigid and composite pavements

WIM data from the M25 and M180 West were used to calculate the predicted Design Traffic over 20 years using a range of power law exponents. The results are presented in Figure 4.1 as a percentage of the Design Traffic predicted using the procedure given in HD 24/96.

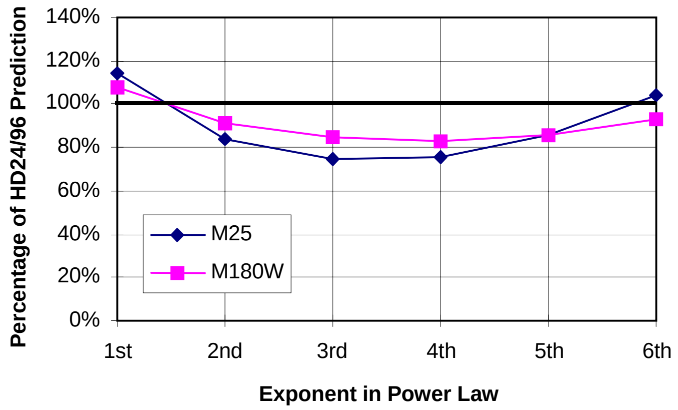


Figure 4.1: Predicted Design Traffic using different exponents (expressed as a percentage of Design Traffic predicted using the HD24/96 method)

The results showed that the predicted design traffic tended to increase as the exponent varied from 4.

They also calculated average vehicle wear factors. Initial results from five WIM sites showed significant differences between sites. The work was extended to include data for the first quarter of 1996 from 15 WIM sites. The calculated wear factors are shown in Table 4.1.

4.3 Aggregate damage approach

The aggregate damage approach takes into account the pavement response as well as vehicle loading.

The single pass methodology developed by Cebon (1993), estimates pavement wear due to the passage of a single vehicle. The procedure simulates a vehicle travelling along the pavement with dynamic loads produced by a simulated roughness along the road surface. The responses of the pavement under these dynamic loads are calculated at discrete points along the pavement and these responses used to predict pavement wear.

An example of a use of the Single Pass methodology was given by Gillespie et al (1993) who conducted a parametric study covering vehicle factors, tyre factors and pavement factors. From this study, average vehicle wear factors for each mode of failure and each vehicle type could be determined. Collop (1999) converted the average wear factors from the US study, using a typical UK fleet (see Table 4.1).

4.4 Summary of recent studies

The calculated values from the three studies (TRL, Hakim and Thom, and Collop) are shown in Table 4.1 together with the wear factors in HD 24/96.

Table 4.1: Comparison of Proposed Wear factors with HD24/96

Vehicle Type	Wear factors					
	HD24/96	TRL (1997)	Hakim and Thom (1998)	Collop (1999)		
				Flexible pavements		Rigid pavements
				Rutting	Fatigue	
2-axle rigid	0.34	0.40	-	1.16	1.46	0.68
3-axle rigid	1.70	1.26	1.16	2.32	2.39	1.29
3-axle artic.	0.65	0.65	0.39	1.79	1.63	0.68
4-axle rigid	3.00	2.80	1.75	2.85	3.12	2.12
4-axle artic.	2.60	1.00	0.84	2.71	2.26	1.10
5-axle artic.	3.50	2.50	2.02	3.70	3.94	2.65
6-axle artic.	3.50	1.69	1.78	3.94	3.03	1.48

The variability between wear factors is due to the use of different data sources, different methods of computing the wear factors and changes in traffic.

5 Non UK methods of incorporating traffic loading into pavement design

This section reviews methods used to determine design traffic in various countries. It was produced by consulting design manuals. The methods demonstrate alternative perspectives to dealing with traffic loading and highlight aspects which are considered to be important.

5.1 Australia

Methods used in the AUSTROADS design manual (AUSTROADS, 1992) are summarised;

Method 1

The AUSTROADS design manual contains different 'standard' axle loads for different configurations of axles, L_{Si}, as shown in Table 5.1.

Table 5.1: Axles loads which cause equal wear

Axle configuration	Single	Single	Tandem	Tridem
Wheel type	**Single**	**Dual**	**Dual**	**Dual**
Load (kN)	53	80	135	181

Different exponents are used to calculate factors for asphalt, cement bound material and the subgrade (known as F_A, F_C and F_S). Products of these factors and the number of axles for each axle group are summed to produce the number of 'standard' axles.

Method 2

Alternatively, an equivalent daily traffic, $N_{E,}$ can be calculated:

$$N_E = N_{A1}F_1 + N_{A2}F_2 + N_{A3}F_3 + N_{A4}F_4$$

N_{Ai} = daily counts of axles for axle group i.
F_i = Factor indicating 'standard' axles dependent on axle type, geographical area and road function type.

N_E is then converted into the number of 'standard' axles for different parts of the pavement using a multiplier of 1.1 for asphalt (N_{SA}) and the subgrade (N_{SS}) and 20 for cement bound material (N_{SC}).

The design traffic is then determined by multiplying the daily figure by a growth factor incorporating the expected annual traffic growth and the design period.

Method 3

The annual average daily traffic (AADT) can be used to produce an equivalent daily traffic, N_E:

$$N_E = \frac{AADT \times F \times C}{100}$$

F = Factors indicating 'standard' axles per commercial vehicle dependent on road function and geographical area.
C = Percentage of commercial traffic

5.2 New Zealand

The New Zealand method (Transit, 2000) closely follows the AUSTROADS design manual methods 2 and 3. However, specific 'standard' axle factors (F and F_i) have been determined for New Zealand conditions and areas. These adopt a multiplier of 10 rather than 20 for the modification of N_E to cement bound materials.

5.3 United States (AASHTO)

The AASHTO method (AASHTO, 1993) for calculating design traffic uses load equivalence factors which convert the axle load into a change in the Pavement Serviceability Index (PSI) equivalent to that produced by an 18 kip (80kN) axle. These load equivalence factors were determined from the original AASHO Road Test (Highways Research Board, 1962). Later, tridem axles, which were not included in the original test, were added using more recent research. Load equivalence factors are a function of pavement type (flexible or rigid), thickness (structural number or slab thickness) and terminal serviceability, p_t (the required PSI at the end of the design period). If a higher p_t is required, the load equivalence factors increase, inflating the design ESALs (Equivalent Standard Axle Loads).

The design traffic, determined from counts of current traffic multiplied by a growth factor for the design period, is multiplied by the load equivalence factor to give the design 'standard' axles which are then summed to give design ESALs. The design traffic includes all types of vehicle (passenger cars and vans through to heavy goods vehicles).

Finally an adjustment is made for the number of lanes in the road.

5.4 France

The French method (LCPC, 1997) converts traffic counts into a number of equivalent 130kN axle loads, NE, for each layer in the pavement construction. NE is a product of a cumulative number of heavy vehicles (payload greater than 5 tonnes), N and a co-efficient of aggressiveness, CAM.

$$CAM = \frac{1}{NPL}\left[\sum_i \sum_{j=1}^{3} k_j n_{ij} \left(\frac{P_i}{P_0}\right)^{\alpha}\right]$$

where:

NPL = Number of heavy vehicles
k = Co-efficient dependent on axle type j and pavement type,
n = Number of axles of type j and load class Pi

The exponent α is 5 (5^{th} power law) for bituminous pavements and 12 for other pavement types. Alternatively, CAM can be assumed for medium and high traffic volumes depending on the material and layer type, as in Table 5.2

Table 5.2. Mean aggressiveness of traffic

Material	CAM
Bituminous layers on composite and inverted structures / Bituminous layers of 20cm thick or more	0.8
Bituminous pavements over 20cm thick / Untreated granular layers and subgrade	1.0

N is determined from an average annual daily flow, ADM, which has been adjusted for the road type (see Table 5.3) and a traffic growth factor.

Table 5.3 Correction to ADM for the numbers of lanes in rural locations

Number of lanes in each direction	Percent of heavy vehicles in lane 1
2	90
3	80 (65)

( ) is for orbital roads around cities

5.5 Netherlands

The Dutch system for determining equivalent traffic gives an expression of the number of equivalent 100kN ‘standard’ axles, N_{eq}, using the following equation.

$$N_{eq} = V \times W \times F_r \times F_{nb} \times F_v \times D_v \times G$$

Where V = Number of freight vehicles

W = Number of working days in a year

F_r = Factor for the number of lanes

F_s = Factor for lane width

F_{nb} = Factor for the percentage of wide base tires (dependent on pavement thickness)

F_v = Factor for freight vehicle speed

D_v = Freight vehicle damage ratio (average number of equivalent 100kN ‘standard’ axles per freight vehicle)

G = Traffic growth factor

The Dv factors are analogous to the vehicle wear factors in HD24/96. The Netherlands uses a three class system to rate vehicles (see Table 5.4).

Table 5.4 Freight vehicle damage ratio for different traffic types

Traffic Category	Dv
Light freight traffic	1.2
Medium freight traffic	1.6
Heavy freight traffic	2.0

5.6 Discussion

In four of these five design methods, the load equivalence factor (vehicle wear factor) depends on the type of pavement construction. The UK wear factors are independent of the pavement design; the different responses of different construction types being taken into account in the design charts. Both are valid approaches but it is not possible to adopt the method of calculating wear factors from one approach and apply it to the pavement design method from the other approach.

Some of the above methods also take into account pavement thickness. This means that design becomes an iterative process, where the initial design thickness is estimated and analysis is then undertaken to see if this thickness is sufficient for the design vehicle loading. If not, the thickness will be increased and the analysis repeated. This is a perfectly valid method but it is perhaps simpler to calculate the design traffic separately and to apply this to any type of pavement construction to obtain the correct thickness.

Having different wear factors for different types of pavement construction could inhibit innovation, as new wear factors would need to be established for each new material or new method of construction. It is considered preferable to have wear factors which can be given in a specification for road construction, independent of the construction materials and layer thicknesses selected. There is therefore no advantage in adopting any of the methods reviewed here.

Lane width and geographical area are also inputs in some of the methods summarised above. These factors are discussed in the following sections.

6 Vehicle parameters affecting pavement wear

Various studies have suggested that, in addition to the axle load, vehicle parameters such as tyre configuration, axle configuration and suspension should be taken into account when calculating vehicle wear factors. In this Section, various parameters are examined and recommendations are made as to whether they should be used in deriving revised vehicle wear factors.

6.1 Axle load

The connection between axle load and pavement wear has long been recognised. The AASHO Road Test showed that structural pavement wear was proportional to the fourth power of the axle load.

While more recent work has suggested that the 4^{th} power law may not be applicable in all cases, it is generally accepted that axle load is a fundamental parameter that must be used in any future method of calculating wear factors.

6.2 Dynamic loading and vehicle suspension

A study in the USA by Smith (1991) found that dynamic loading (variations in the applied axle load due to interaction between the vehicle suspension and pavement profile) can increase the peak axle load by a factor of two or more. These peak dynamic wheel loads can be concentrated at specific locations on the road (Collop, 1994). This ‘spatial repeatability’ effect can result in average peak loads of up to 1.4 times the static loads; the size of these peak loads being influenced by the speed of the vehicle and by the roughness of the road. Collop concluded that spatial repeatability could influence pavement failure and therefore should be considered in future calculations of vehicle wear.

The type of suspension can affect the dynamic loading on the pavement and thus pavement wear. This effect is acknowledged in legislation - the heaviest vehicles are encouraged to use ‘road-friendly’ air suspension systems. However, the DIVINE project (OECD, 1998) showed that the benefits of road-friendly suspension are only fully achieved if the suspension systems are maintained to a high standard - poorly damped air suspensions can increase the dynamic load and thus pavement wear. This work recommended that concessions for road-friendly suspension systems should only be given if policy makers have confidence in their long-term in-service performance.

The vehicle wear factors in HD 24/96 were derived from measurements of real traffic on motorways and trunk roads and so already take some dynamic loading into account. However, dynamic loading could be of far greater importance on less major roads that are not maintained in such a good surface condition.

It is recommended that vehicle wear factors continue to take dynamic loading into account and that an element of conservatism is built into the wear factors as they will be used to derive design traffic for all roads, not just heavily trafficked motorways and trunk roads where dynamic loading is likely to relatively low.

6.3 Tyre Configuration

TRL has examined the pavement response (induced strain) when different types of tyre were tested in TRL's Pavement Test Facility. It was found that the dimensions of the tyres had a negligible effect on pavement responses measured deep in the structure. Although some differences were detected between single and dual tyres, the differences diminished with increasing pavement thickness. However, it was observed that surface rutting did vary according to the dimensions of the single tyres. It was concluded that the response of the surfacing is sensitive to the type of tyre applying the load but that the effect of tyre type diminishes deeper in the pavement thus there will be little effect on structural deterioration of the pavement.

Research was also carried out for European COST Action 334 (Cost Action 334, 2002) to quantify the relative wearing effects of a range of types of tyre (dual, wide single, single) on a variety of flexible pavements. It was found that tyre parameters had no effect on structural rutting in thick pavements but on thinner pavements dual or wide base single tyres caused slightly less structural rutting than standard single tyres. In terms of primary (surface) rutting, dual tyres with unequal load sharing between the two tyres were found to be most aggressive - a significant number of dual assemblies on drive axles had unequal load sharing between the two tyres. Very wide based single tyres appeared to cause marginally less surface rutting than either single or dual tyres.

In summary, tyre configuration has more effect on the pavement surface than on structural wear. Currently the main use of vehicle wear factors is to determine the structural requirements for pavements thus tyre configuration is not a factor which should be included in calculating revised wear factors.

6.4 Bogie Configuration

Some of the design methods include different wear factors for single, tandem and tridem axles (i.e. single axles and close-coupled bogies with 2 and 3 axles respectively). Analysis has shown that the stresses and strains in the pavement are affected not merely by the individual axle loads but by the proximity of the axles to each other - closely placed axles may amplify the peak stresses and strains. The extent to which this happens, and the effect in terms of structural wear, will depend on the pavement construction and thickness. For jointed concrete pavements the critical factor is the maximum load on any one slab and this will also be affected by closely spaced axles.

HD 24/96 did not take bogie or axle group configuration into account. Methods which take it into account either result in virtually identical vehicle wear factors to those used in the UK or in very different wear factors for rigid pavements – possibly due to the critical factor being the loading applied towards the edge of a concrete slab. The disadvantage of adopting different wear factors for different types of pavement has been discussed in Section 5.6.

The effect of the bogie configuration will also depend on axle spacing. Quantifying the exact effect would be difficult. It recommended that wear factors err on the side of caution and do not result in pavements which are less robust than those currently in use, which have withstood the test of time and use.

6.5 Lifting Axles

Lifting axles reduces the number of tyres in contact with the pavement, thus reducing both the rolling resistance of the vehicle and tyre wear. The load on the remaining axles is increased.

A theoretical study was carried out to assess the impact of lifting axles. The maximum impact was when the vehicle was fully laden – lifting an axle approximately doubled the vehicle wear factor for a 5-axle articulated vehicle. However, this is unlikely to occur as operating vehicles at these large axle loads could lead to excessive vehicle and tyre wear, and may compromise the safety of the vehicle. It was estimated that road wear would be increased by 10 per cent if operators always lifted axles when it is legal to do so. If axles are lifted only when vehicles are unloaded, the impact on road wear would be negligible.

However, if Weigh-In-Motion (WIM) measurements are used to calculate vehicle wear factors, the axle loads of vehicles with lifted axles would be automatically taken into account (WIM devices classify vehicles by the number of axles in contact with the pavement).

6.6 Vehicle Speed

Asphalt materials are visco-elastic. This means that their behaviour is sensitive to the rate at which they are loaded. Consequently vehicle speed will have an influence on the wear of pavements with asphalt surfacing.

The speed at which a vehicle traverses a pavement depends on many factors including the gradient, weather conditions, proximity to junctions and traffic flow. Given these factors, attempting to estimate a representative vehicle speed is problematic and projections of future vehicle speeds may lead to considerable error. Vehicle speed will have a greater impact on the surfacing than the pavement structure, especially for thicker pavements.

Due to the problems in defining vehicle speed and its limited effect on the pavement structure, it is recommended that it is not considered in any new method of calculating structural pavement wear. However, if serviceability factors are required, vehicle speed may need to be considered.

6.7 Recommended Vehicle Parameters to be included when calculating VWFs

The vehicle parameter recommendations are summarised below:

- Axle load – this is a fundamental parameter that must be used in any future method of calculating vehicle wear factors.

- Vehicle suspension - it is recommended that this is not taken into account due to difficulties in quantifying the effect in the long term. However, the wear factors must include an allowance for detrimental effects of dynamic loading.

- Tyre Configuration Factors – although these may be a useful means of looking at the effect of changes in tyre use, they are likely to have more effect on pavement surfaces than on structural wear. It is recommended that they are not considered in deriving revised vehicle wear factors.

- Axle configuration – due to the variation in axle spacing, difficulties in quantifying the effect on pavement wear and different effects for different pavement types, it is recommended that axle configuration is not included in the revised method of deriving pavement wear factors. A conservative approach should be used to take account of the possible detrimental effect of changing axle groupings.

- Lifting axles – these may have a significant effect on wear factors, and it is recommended that they are taken into account. However, the axle loads of vehicles with lifted axles would be measured by Weigh-In-Motion (WIM) devices and would be implicitly accounted for if WIM measurements are used to derive vehicle wear factors

- Vehicle speed - it is not practical to include vehicle speed in deriving structural wear factors, though it may need to be taken into account when serviceability is considered.

7 Non-vehicle factors affecting pavement wear and calculation of design traffic

7.1 Pavement wear factors

Some methods of calculating wear factors include non-vehicle factors, such as road construction type, lane width and geographical location (see Section 5).

7.1.1 Power Law and Pavement Construction

The AASHO experiment found that for both flexible and rigid pavements the wearing effects was approximately proportional to fourth power of the axle load (Highway Research Board, 1962). Work carried out in the UK on experimental roads, looking at the wearing effects of traffic with a mixed range of axle loads, found that the exponent varied between 4.1 and 6.6 depending on the construction of the pavement and the axle loads (Addis and Whitmarsh, 1981).

Collop (1994) suggested that for thick pavement structures, which tend to fail by rutting within the bituminous layers, a 1st power law may be more reasonable. This is supported by research by Leykauf (1998), who recommended a power of 1.5 for 'flow rutting' of asphalt.

A US Department of Transportation Federal Highway Administration report (FHWA, 1982) proposed different exponents depending on the type of pavement deterioration. The exponents for flexible pavements ranged from 1.30 (alligator cracking) to 4.37 (serviceability loss) and those for rigid pavements from 0.67 (faulting) to 5.48 (cracking).

Autret et al (1987) presented data from the LCPC test track at Nantes, which gave exponents of 1.3 to 3.1 for cracking of flexible pavements and 8.2 to 9.6 for rutting; while Patterson (1985) suggested an exponent of 2 for cracking and 4 for rutting. The National Association of Australian State Road Authorities Pavement Design Guide (NAASRA, 1987) makes use of a 4th power law for thinly surfaced asphalt pavements, a 5th power for fatigue cracking of thicker pavements, an 18th power for cracking of cement bound layers and a 7.14th power for subgrade deformation. In France (Bowskill et al, 1999) a 5th power is used for asphalt fatigue.

Table 7.1 summarises the range of power law exponents which the literature review identified.

The exponents tend to be higher for rigid pavements than for flexible pavements. The non-structural modes of deterioration generally have an exponent much lower than that for structural modes of failure.

One problem regarding such power law relationships is that they have been calculated assuming that deterioration is inflicted by traffic loading alone, whereas it is known that environmental effects can also have a large effect (Nesnas et al, 2002).

Hakim and Thom (1998) investigated the sensitivity of design traffic to the power law exponent (see Section 4.2), examining the range 1 to 6. They found that, within the range 2nd power to 5th power, the effect was surprisingly small when applied to real traffic distributions. With a low exponent, the influence of the large number of light vehicles became much more significant, leading to an increased computed traffic loading. With a high exponent, although the lighter vehicles could be ignored, the influence of the few very heavy axles led to an increase in computed traffic loading. The 4th power approach gave close to a minimum but the differences, from 2nd to 5th power, were only of the order of 10 per cent change in design traffic.

Table 7.1. Power law exponents for different modes of deterioration

Mode of Deterioration	Range of Exponents
Flexible Pavements	
Non Structural rutting	1.0 - 1.5
Cracking	1.3 - 3.1
Serviceability	4.4
Rutting	4.0 - 9.6
Asphalt fatigue	4-5
Rigid Pavements	
Rigid pavement cracking	5.5 - 18.0
Faulting at joints	0.7
Subgrade	
Derformation	4.0 - 7.4

Research has also indicated that wear factors are dependent on the thickness of the pavement (COST Action 334, 2002). However, using different wear factors for different thicknesses would make design an iterative process, with an initial estimate of thickness assumed and revised if calculations showed that it was inadequate. This adds unnecessary complication and it is recommended that pavement thickness is not taken into account in deriving wear factors.

Using different power laws for different constructions and for different modes of deterioration is considered to be impractical. If a contractor wishes to use a novel pavement design that spans the divide between design types, there would be confusion regarding which power laws to use. These problems could be exacerbated when determining traffic for maintenance where there can be different construction types along the same stretch of road.

All current UK designs in HD26/01 were calibrated to design traffic calculated using vehicle wear factors based on the 4^{th} power law. Thus the design method already implicitly takes into account a pavement construction factor. Adoption of a significantly different power law would mean that the designs would need to be re-calibrated for the different design traffic.

It is recommended that the 4^{th} power law continues to be used for calculating structural vehicle wear factors and that the same wear factors are used whatever the pavement construction type and thickness.

7.1.2 Lane Width

The Netherlands incorporates lane widths into their calculations of pavement wear, based on the theory that a wider lane encourages more lateral wander of traffic within the lane, thus distributing the traffic loading over a wider area. This would result in overall pavement wear being reduced. However, there are a number of points to consider:

- the effect of bends and other features will concentrate the traffic in certain areas of the lane
- lane width may not be regular along a stretch of road
- in the UK the nominal lane width on new trunk roads and motorways is 3.65m, and there is little variation in this
- increased lateral wander may only be applicable in the early life of the pavement - as pavements rut, heavy goods vehicles tend to track in the ruts.

It is therefore recommended that lane width is not incorporated into a new method of calculating pavement wear.

7.1.3 Geographical Effects

Geographical location could have an impact on pavement wear and on the modes of failure, due to local differences in temperature, vehicle movements, vehicle types or degree of loading.

Temperature has a significant effect on the behaviour of pavements. The properties of the asphalt are temperature dependent and significant variations in temperature from one region to another will affect the rates of rutting and cracking of flexible pavements. In rigid pavements, temperature changes affect the movement at joints and any cracks. However, the temperature differences due to location in the UK are not great due to the maritime climate and the relatively small size of the country (compared with Australia where geographical location is taken into account).

Pavement loading in some areas of the UK is relatively high due to the proximity to local facilities (for example a port). In these areas the mix of traffic and the goods carried is very different from the representative UK mix on which pavement design is based. It would be advisable to reflect this in the calculation of the design traffic (these effects will be peculiar to the local area and therefore should be taken into account on a site-specific basis).

Traffic levels are taken into account as part of the design. If there were a significant increase in traffic for a particular local reason, it would normally be included in the design traffic level.

It is therefore recommended that geographical location is not included in the general methodology for the calculation of vehicle wear factors, although it may be taken into account in the specification of surface materials.

7.1.4 Summary of non-vehicle factors to be included in a revision of wear factors

The arguments for including or excluding non-vehicle parameters have been discussed above. In summary it is recommended that:

- the fourth power law should continue to be used for all construction types and thicknesses of pavement
- pavement width should not be taken into account as bends and early life rutting mean the lateral distribution of traffic is not necessarily dependent on lane width
- geographical effects should not be taken into account as there is relatively little temperature variation in the UK; vehicle types and loading conditions may vary due to geographical factors but these will be very local effects and may change considerably over the design life of the pavement.

7.2 Changes to Vehicle Classifications

Since the 1998 revision of vehicle wear factors, there have been changes in the use of heavy goods vehicles. For example, 6-axle articulated vehicles are now common but HD 24/96 included them in the ‘5 or more axle’ category.

The Design Manual for Roads and Bridges includes advice on the Cost / Benefit Analysis (COBA) of road schemes. A critical part of the COBA system is characterisation of traffic using a number of vehicle classes. These classes are similar to those used for determining pavement design traffic but there are notable differences. The COBA system defines vehicles as either light or heavy commercial vehicles; the heavy commercial vehicle category includes all articulated vehicles. In comparison, the HD 24/96 classification for vehicle wear factors placed 3-axle articulated vehicles into a light commercial vehicle group called OGV1.

The use of articulated vehicles with 3 axles has declined over the past decade. It is recommended that these vehicles be classified together with 4-axle articulated vehicles. The combined 3 and 4-axle articulated class of vehicles would be placed into the heavy commercial vehicle category (OGV2).

Table 7.2. HD 24/96 and proposed vehicle classifications

Class	HD 24/96 Classification	Proposed Classification
OGV1	Buses & Coaches 2-axle rigid 3-axle rigid 3-axle artic.	Buses & Coaches 2-axle rigid 3-axle rigid
OGV2	4-axle rigid 4-axle artic. 5+axle artic.	4-axle rigid 3 & 4-axle artic. 5-axle artic. 6-axle artic.

The proposals shown in Table 7.2 would harmonise the classifications between different sections of the Design Manual for Roads and Bridges and more appropriately represent the current commercial vehicle fleet.

7.3 Determination of Traffic Growth Factors

Growth factors relate traffic counts made at a particular time to the total usage (future or past) over a defined design period.

7.3.1 Future Traffic

The National Road Traffic Forecast (NRTF) is published at eight year intervals. These forecasts contain low, medium and high growth estimates of different types of vehicles (cars, light goods vehicles, rigid heavy goods vehicles, articulated heavy goods vehicles and buses) over a 35-year period; the 1997 publication (Department of the Environment, Transport and the Regions, 1997) contained growth figures from 1996 to 2031.

A medium growth trend was used to determine growth factors that could be generally applied. An annual rate of growth was determined from the annual indices between 1996 and 2031 inclusive as shown in Table 7.3.

Although the NRTF document does not precisely reflect the vehicle classifications for OGV1 and OGV2 recommended in this report, rigid heavy goods vehicles have been taken to represent OGV1 while articulated heavy goods vehicles have been taken to represent OGV2. Figure 7.1 shows the calculated growth factors, expressed in a similar form to the advice in the HD 24/96.

Table 7.3 Average annual rate of growth by vehicle type

Vehicle Type	Average annual rate of growth
Rigid	0.9%
Articulated	2.5%

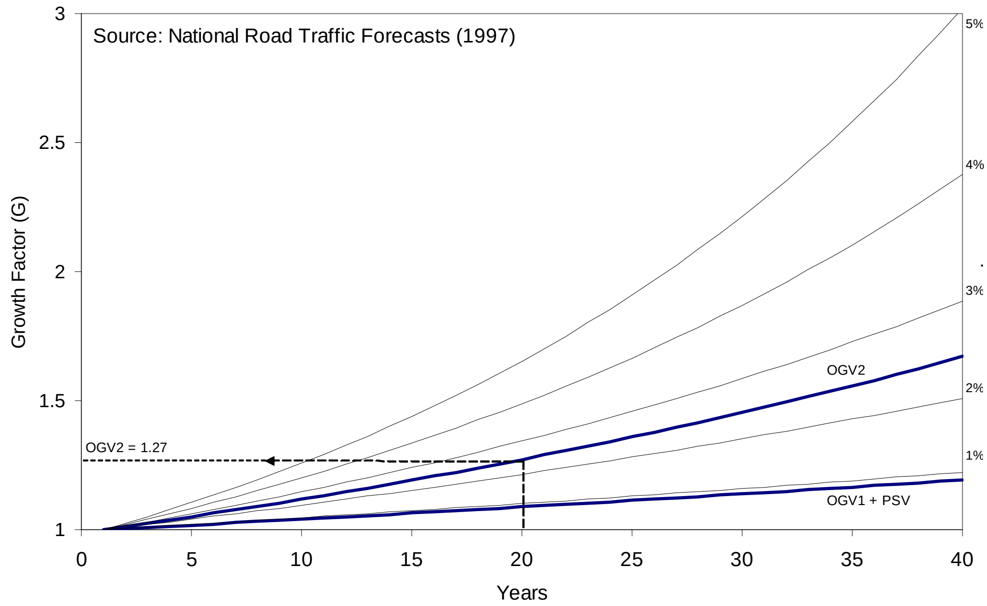


Figure 7.1. Calculated growth factors for future traffic

7.3.2 Past Traffic

Using the same procedure as for the determination of future traffic, the past traffic can be deduced using average annual growth rates. An adjustment has been included for the observed change in gross vehicle weights over the past ten years and the past traffic growth factors are shown in Figure 7.2.

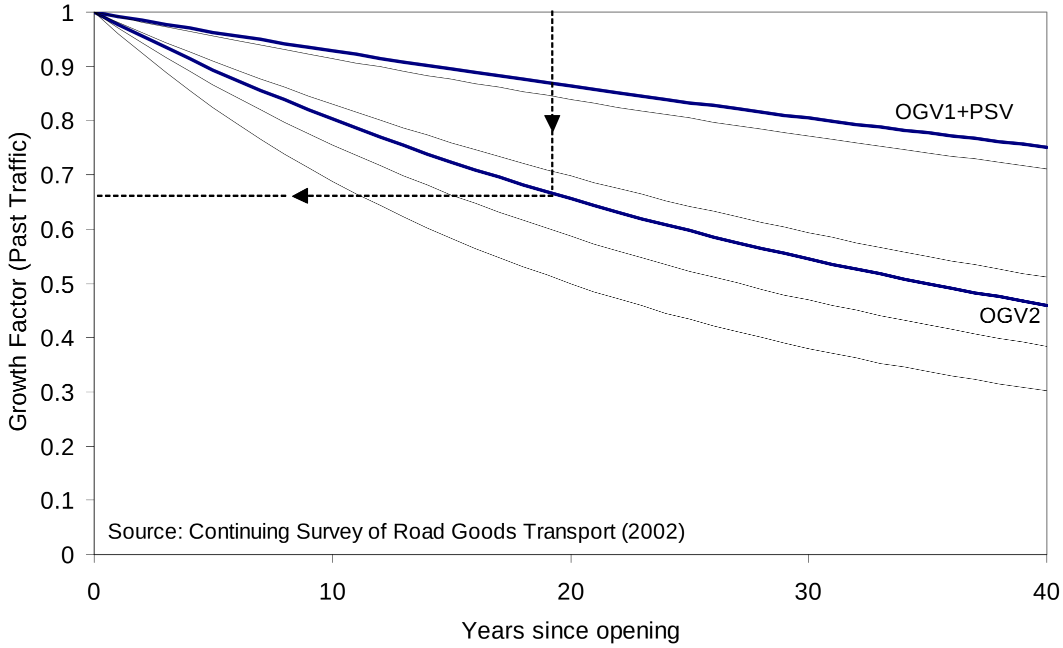


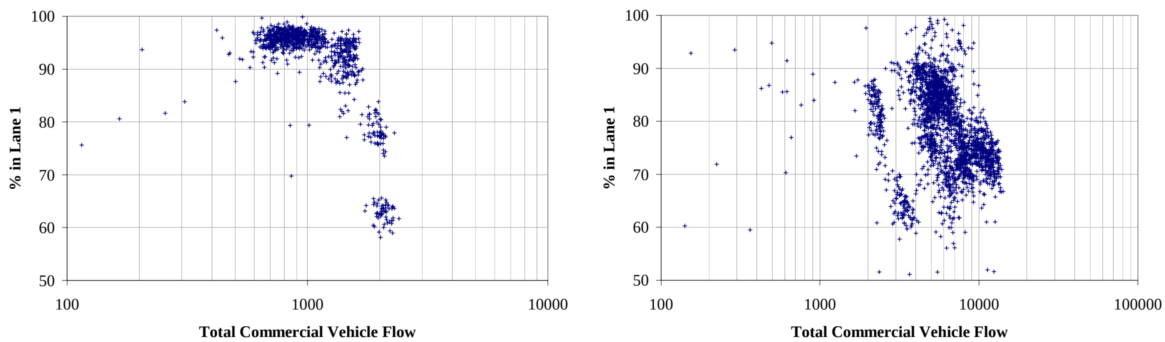
Figure 7.2 Calculated growth factors for past traffic

7.4 Proportion of Traffic in the Main Traffic Lane

The calculation of design traffic includes an estimate of the proportion of the commercial vehicles travelling in Lane 1 of multi-lane roads.

The distribution of traffic across lanes has been reviewed by TRL. Traffic counts were carried out at nine sites, between 1992 and 1995. Three of the sites were on motorways, the rest were on ‘A’ roads.

The proportion of vehicles in the left-hand lane compared with the daily flow of commercial vehicles along the carriageway is shown for two-lane carriageways in Figure 7.3a and three-lane carriageways in Figure 7.3b.



a **b**

Figure 7.3. Lane distribution data for 2 and 3-lane (graphs ‘a’ and ‘b’) carriageways

TRL also examined the lane distribution for 4-lane carriageways. It was concluded that the distribution was more complex than for 2 and 3-lane carriageways and may be highly influenced by the proximity to junctions (at the time of this research, 4-lane carriageways were most common between junctions, with a ‘lane drop’ in lane 1 causing vehicles to use lane 2 as the main traffic lane if there was a short distance between junctions).

The lane distribution on 4-lane dual carriageways was reviewed again in 2003. At this time there were only two core census locations on a 4-lane dual carriageway. These were on the A1(M) between Junctions 15 and 16 (northbound and southbound carriageways). They were more than a mile from any junction and no ‘lane drop’ was present. Data were analysed for a three month period between July and September 2003.

Figure 7.4 shows this data for 4-lane carriageways together with the data for 3-lane carriageways from Figure 7.3b. The chart shows two concentrations of data which represent weekday and weekend traffic; approximately 6,000 commercial vehicles per day for weekdays and 2,000 vehicles per day for weekend traffic.

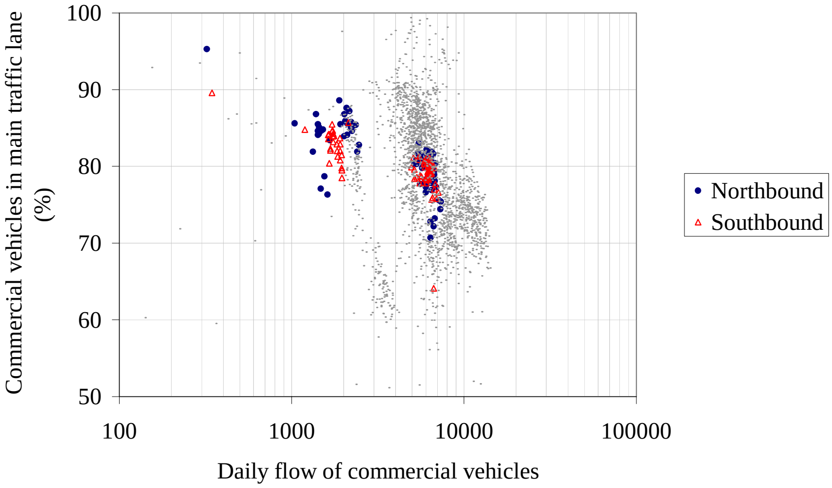


Figure 7.4 Comparison of lane distribution data for 3 and 4-lane dual carriageways

This suggests that where there is no ‘lane dropping’ there is no distinguishable difference between the lane distribution of commercial vehicles on 3-lane dual carriageways and 4-lane dual carriageways.

Further examination of the data shown in Figure 7.3 and the A1(M) data showed that one curve could be derived to represent all the data. The previously assumed difference in heavy traffic lane distribution between 2 and 3-lane sites was caused by only three sites which were unrepresentative of the body of the data. A best-fit curve was created through the majority of the data (excluding those three sites) and is shown in Figure 7.5. The term ‘main traffic lane’ has been adopted because factors such as junction design can result in the majority of commercial vehicle traffic travelling in lanes other than in lane 1.

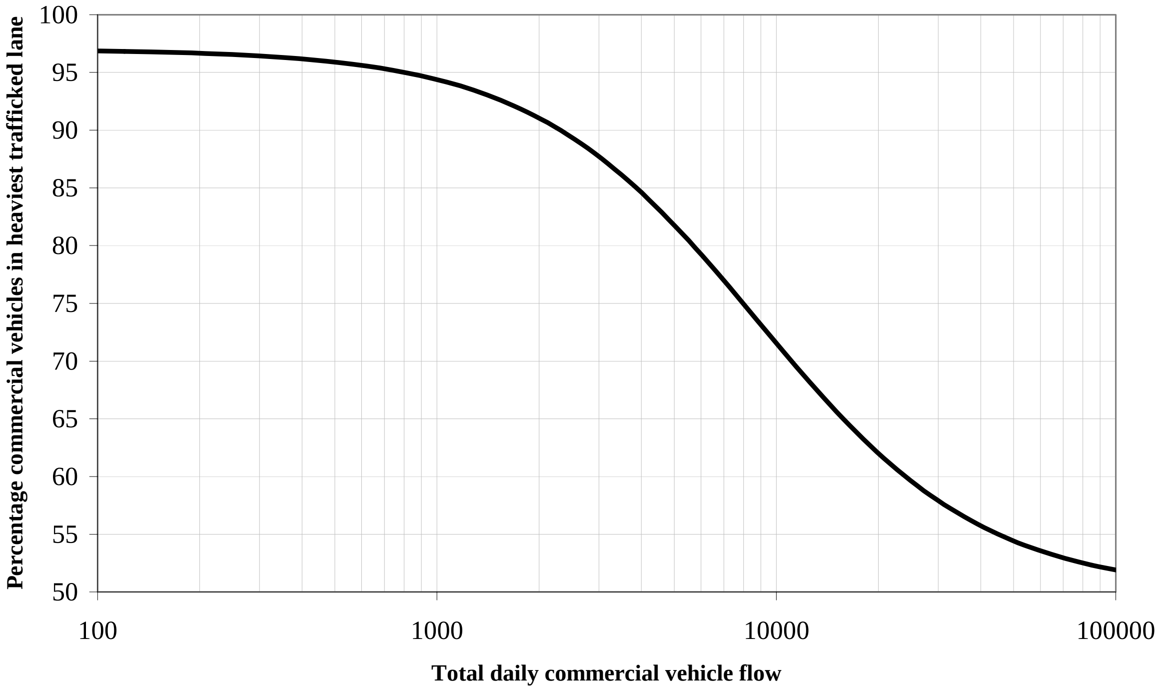


Figure 7.5 Proportion of commercial vehicles in main traffic lane, based on daily flow

The equation of the above curve is:

$$\%\,\text{in main traffic lane} = 47 \times \left[1 - \frac{1}{1 + e^{-3 \times \log\left(\frac{CVF}{8800}\right)}} \right] + 50$$

CVF is the daily commercial vehicle flow in all lanes of the carriageway.

8 Recommended revisions to HD 24/96

8.1 Method of relating pavement deterioration to vehicle loading

As discussed in Section 2, possible generic methods of pavement design are:

- Discrete damage analysis
- Load equivalence
- Traffic classes

The use of simple traffic classes for pavement design is not thought to be viable because it would lead to step changes in design thickness when going from one traffic level to another.

While discrete damage analysis has the potential to accurately model vehicle / pavement interaction it relies on accurate predictions of factors such as temperature and vehicle speed. It also relies on accurately defining pavement deterioration in terms of pavement response. It was considered that there would be no advantage in using this method compared with the current load equivalence method.

It is therefore recommended that there should be no basic change in the current UK method for producing wear factors. The load equivalence method could be adapted, using the Eisenmann stress equation, to take account of factors other than axle load, if this becomes desirable.

8.2 Parameters affecting wear factors

Vehicle and non-vehicle parameters which may affect wear factors were discussed in Sections 6 and 7. The vehicle parameters which were considered were:

- Axle load
- Suspension
- Tyre configuration
- Speed
- Axle configuration
- Lifting axles

Axle load is fundamental and needs to be part of any wear factor calculation. It is recommended that the other factors should not be included in the calculation of wear factors but that an element of conservatism should be incorporated to allow for changes in suspensions, axle configurations, etc.

The power law was also discussed and because variations of construction type and thickness are taken into account in the current design methodology, it is recommended that the fourth power law should continue to be used for all construction types and thicknesses of pavement.

Non-vehicle factors discussed were:

- Pavement width
- Geographical effects

It is recommended that pavement width should not be taken into account as bends and early life rutting mean that the lateral distribution of traffic is not necessarily dependent on lane width. Also geographical effects should not be taken into account as there is little temperature variation in the UK. Vehicle types and loading conditions may vary due to geographical factors but these will be very local effects and may change considerably over the design life of the pavement.

It was concluded that revised wear factors should be derived using the fourth power of axle loads.

8.3 Lane distribution

The estimated proportion of traffic in the heaviest trafficked lane has been discussed in Section 7. It is recommended that the lane distribution curve in HD24/96 be revised, as illustrated in Figure 7.5. This will more accurately reflect the current situation and can be easily included into the method without any direct impact on other parts of the design documents.

8.4 Vehicle classifications

Originally the vehicle classifications in DMRB were the same for HD 24 and COBA. The classifications in COBA have since been changed. It is recommended that HD 24 be adjusted to reflect the latest classification in COBA.

8.5 Whole life costs and design period

Changes in wear factors, and thus in design traffic, may lead to changes in the design thickness of new pavements and the maintenance requirements of existing pavements. A whole life costing exercise was carried out using the COMPARE (Abell, 1993) model to investigate the effect of changes in design traffic and to ascertain the most cost effective design life.

The economic analysis suggested that there are whole life cost benefits in building pavements for longer design lives. For a small increase in the initial investment, economic rewards are collected through longer periods between structural maintenance and, more importantly, reduced user costs as a result of delays at road works. Taking a conservative approach should also ensure that pavements can cope with overloaded vehicles, exceptional vehicles and other changes which may increase axle loads.

The results also indicated that selecting a design period of less than 40 years created additional whole life costs, thus a standard design period of 40 years is recommended.

8.6 Data sources

Cost-effective sources of data on vehicle loads are required for calculating wear factors. Possible data sources are weigh-in-motion (WIM) devices, ‘static’ axle weight surveys and the Continuing Survey of Roads Goods Transport (CSRGT). These are reviewed in Appendix A and the advantages and disadvantages of each are discussed. CSRGT data gives no information on axle loads and there may be a tendency for operators to understate vehicle loads. ‘Static’ weighing is expensive and provides no information on actual dynamic effects loading. It was therefore decided that WIM data should be used to calculate revised vehicle wear factors. These factors will implicitly take into account some dynamic effects and the impact of lifting axles.

8.7 Summary

The following recommendations are made:

- The current vehicle wear factors should be revised. The recommended method of deriving new wear factors is to use a load equivalence method and an exponent of 4.
- Wear factors should be derived from weigh-in-motion data. This will implicitly capture the effect of lifting axles and some dynamic loading.
- Changes to the method of converting vehicle wear factors to design traffic are recommended. These include revising the vehicle classification and adopting revised lane distribution curves.

9 Determination of Revised Vehicle Wear Factors

The use of weigh-in-motion (WIM) data to calculate vehicle wear factors has some distinct advantages over other methods.

- It provides an unbiased sample of vehicles (drivers are unaware that their vehicles are being weighed)
- A very large number of vehicles can be weighed
- It provides and almost continuous measure of the traffic enabling trends to be easily deduced
- Data sourced from WIM devices are a measure of the actual axle loading on the pavements, including some dynamic loading
- The impact of lifted axles is taken into account (for example, a 6-axle vehicle with one axle lifted would be classified as a 5-axle vehicle)
- The data are readily available from a number of core census locations
- Vehicle wear factors can be produced relatively easily using a computer program

9.1 Vehicle wear factors determined from WIM devices located at Core Census locations

The derivation of vehicle wear factors based on data from WIM devices at core census location is given in Appendix B. This analysis used data from 12 WIM sites over a 10 month period between January and October 2003.

Previous research found variations between different WIM sites. This can be due to the calibration of the sensors, the time since calibration, the geometry of the site, the pavement surface and / or the distribution of vehicles traversing a particular site. Hakim and Thom (1998) suggested that 15 WIM sites would result in an average error in actual pavement thickness of approximately 7%.

The WIM data were used to calculate the vehicle wear factor for each vehicle. The average vehicle wear factors are presented in Table 9.1.

Table 9.1. Summary of Vehicle Wear Factors from Core Census Locations

Vehicle Class	Number of vehicles analysed (million)	Vehicle Wear Factors		
		Minimum*	Maximum*	Average
Buses & Coaches	0.3	1.17	3.14	1.97
2-axle rigid	4.2	0.14	0.60	0.28
3-axle rigid	0.3	1.06	2.84	1.72
4-axle rigid	0.2	1.19	4.23	2.28
3 & 4-axle articulated	1.1	0.62	2.00	1.24
5- axle articulated	3.7	1.26	3.08	2.18
6-axle articulated	2.1	2.05	4.48	2.79
OGV1 + Buses & Coaches	4.8	0.29	0.84	0.48
OGV2	7.1	1.60	3.29	2.22

* maximum and minimum values of the average vehicle wear factor at one site

9.2 Comparison of wear factors in HD 24/96 with wear factors from WIM

The average WIM wear factors are compared with those in HD 24/96 in Table 9.2.

Table 9.2 Comparison of wear factors from WIM with HD 24/96

Vehicle Class	Wear factors from HD 24/96	Wear factors from WIM
Buses & Coaches	1.30	1.97
2R	0.34	0.28
3R	1.70	1.72
4R	3.00	2.28
3A & 4A	0.65 (3A) 2.60 (4A)	1.24
5A	3.50	2.18
6A	3.50	2.79
OGV1 + Buses & Coaches	0.6	0.48
OGV2	3.0	2.22

The wear factors derived from the WIM sites tend to be lower than those used in HD 24/96.

9.3 Recommended revised wear factors

The vehicle wear factors in the HD24/96 detailed method were 0.6 for OGV1 and 3.0 for OGV2, giving a weighted average of 2.03. The equivalent factors calculated using WIM data were 0.5 and 2.2 respectively, giving a weighted average of 1.52. A factor of approximately 1.33 would link the WIM wear factors with those in HD24/96. This is similar in magnitude to the factor of 1.3 used by Robinson to calculate the wear factors used in HD24/96 (see Section 3). Robinson applied this factor to make the wear factors derived from static axle weights consistent with those calculated using dynamic measurements. Whilst the current WIM systems measure instantaneous dynamic axle loads, the sensors are calibrated against static axle weights and therefore a similar dynamic factor is appropriate (the original dynamic weighbridges were calibrated using a directly applied load).

It is recommended that the wear factors used for new construction are multiplied by a further safety factor to guard against the uncertainties in estimating future pavement wear. Use of safety factors (multipliers to account for uncertainty) is a well established principle in construction design. Safety factors tend to be relatively low where risk is low and the reliability of inputs to the design process is high. They are higher where the risk is higher, and / or the inputs to the design process are less certain. This is the case for construction of a new pavement where the traffic which will use it over a 40 year period is very uncertain. It is recommended that a multiplier of 2.0 (rather than 1.33) is used for new construction. This would results in pavement designs approximately equivalent to those using HD24/96. The resulting recommended wear factors are shown in Table 9.3.

Table 9.3 Recommended Vehicle Wear Factors

Vehicle Class	Weighted average factor	Proposed Vehicle Wear Factors	
		Maintenance (W_M)	New design (W_N)
Buses & Coaches	2.0	2.6	3.9
2-axle rigid	0.3	0.4	0.6
3-axle rigid	1.7	2.3	3.4
4-axle rigid	2.3	3.0	4.6
3/4-axle artic	1.2	1.7	2.5
5-axle artic.	2.2	2.9	4.4
6-axle artic.	2.8	3.7	5.6
OGV1	0.5	0.6	1.0
OGV2	2.2	3.0	4.4

10 Conclusions

Following a review of the method of estimating traffic loading for the design of road pavements set out in HD24/96, it was concluded that:

- A revised vehicle classification system should be used to reflect the current use of heavy goods vehicles. This would also unify vehicle classifications within the Design Manual for Roads and Bridges.
- A revised set of traffic growth estimates should be used.
- A revised lane distribution curve should be used. This defines the proportion of traffic to be carried in the main traffic lane (rather than Lane 1).
- A revised method for the derivation of vehicle wear factors should be used for new construction and maintenance purposes. This is consistent with the wear factors in HD24/96.

11 Recommendation

The work reported in this report concentrated on the factors used to estimate structural road wear. UK heavily-trafficked fully flexible roads are designed to be long-life, and it is assumed that wear will be confined to the surface layers. If the surface layers are replaced before cracking penetrates to the layers below, there should not be any structural deterioration. Serviceability wear (including surface rutting, cracking and deterioration of the pavement profile) then becomes relatively more important. It is recommended that the factors influencing serviceability wear should be examined in greater detail.

12 Acknowledgements

The work described in this report was carried out in the Infrastructure and Environment Division of TRL Limited and at Scott Wilson Pavement Engineering Limited. The authors are grateful to Mr W Newton who carried out the quality review and auditing of this report; to Dr K Nesnas who calculated vehicle wear factors from the CSRGT data; and to the Transport Statistics Group of the Department for Transport who provided WIM data.

13 References

AASHTO (1993). AASHTO guide for design of pavement structures. American Association of State Highway and Transportation Officials. Washington DC.

ABELL RA (1993). Whole life costing of pavements. Asphalt and Coated Macadam Association Annual Seminar. Solihull.

ADDIS RR and WHITMARSH RA (1981). Relative damaging power of wheel loads in mixed traffic. TRRL Laboratory Report 979. Crowthorne: Transport and Road Research Laboratory.

AUSTROADS (1992). Pavement Design - A guide to the structural design of road pavements. AUSTROADS, NSW, Australia.

AUTRET P, BAUCHERON DE BOISSOUDY B and GRAMSAMMER JC (1987). The circular test track of the Laboratoire Central Des Ponts et Chaussees (LCPC) Nantes - first results, Sixth International Conference Structural Design of Asphalt Pavements, Ann Arbor, Michigan, pp 550-561.

BOWSKILL G, HERBST G and SAID S (1999). Choice of materials and design for severe traffic and climates, PIARC.

CEBON (1993) Interaction between heavy vehicles and roads, Technical report, Cambridge University Engineering Department.

COLLOP AC (1994). Effect of Traffic and Temperature on Flexible Pavement Wear, PhD Thesis, University of Cambridge.

COLLOP AC (1999). Investigating the requirements for wear factors and the supply of WIM data: Objective 3 Report; Alternative methods of using traffic data in pavement design. Report by Scott Wilson Pavement Engineering to HA.

COST Action 334 (2002). Effects of Wide Single Tyres and Dual Tyres. Directorate General for Energy and Transport, European Commission. www.cordis.lu

CURRER EWH (1974). Commercial Traffic Studies. TRRL Laboratory Report 628. Transport and Road Research Laboratory, Crowthorne, UK.

CURRER EWH and O'CONNER MGD (1979). Commercial traffic: its estimated damaging effect, 1945 - 2005. TRRL Laboratory Report 910. Crowthorne: Transport and Road Research Laboratory.

DEPARTMENT OF THE ENVIRONMENT, TRANSPORT AND THE REGIONS (1997). National Road Traffic Forecasts (Great Britain) 1997. Department of the Environment, Transport and the Regions.

DESIGN MANUAL FOR ROADS AND BRIDGES. Design Manual for Roads and Bridges. The Stationery Office Ltd.

HD24/96: Traffic Assessment (DMRB 7.2.1)

HD24/06: Traffic Assessment (DMRB 7.2.1)

HD25/94: Foundations (DMRB 7.2.2)

HD26/01: Pavement Design (DMRB 7.2.3)

The Application of the COBA Manual (DMRB 13.1.0)

EISENMANN J, BIRMANN D and HILMER A (1986). Effects of commercial vehicle design on road stress - research relating to roads. Strasse und Autobahn 37 (1986) No 6, Kirschbaum Verlag, Bonn. pp 238-244.

FHWA (1982). Final Report on the Federal Highway Cost Allocation Study, US Department of Transport.

FRITH BA and BARBOUR IA (1992). Goods vehicle surveys at four WIM pre-selection sites (1990/1991). TRL Research Report 369. Transport Research Laboratory, Crowthorne, UK.

GILLESPIE TD, KARAMIHAS SM, SAYERS MW, NASIM MA, HANSEN W, EHSAN N and CEBON D (1993). Effects of heavy-vehicle characteristics on pavement response and performance. Report 353, Transportation Research Board, Washington D.C.

HAKIM BA and THOM NH (1998). Investigating the requirements for wear factors and the supply of WIM data: Objective 2 Report; Examination of VWF production, Report by Scott Wilson Pavement Engineering to HA.

HIGHWAY RESEARCH BOARD (1962). The AASHO Road Test: Pavement Research. Special Report No. 61E, National Academy of Sciences, National Research Council, Publication 954, Washington D.C.

LCPC (1997). French Design Manual for pavement structures. Laboratoire Central des Ponts et Chaussées, Paris.

LEYKAUF G (1998). Anforderungen an Fahrbahnbefestigungen im Verlauf des letzten und des nächsten Jahrzehnts, Strasse und Autobahn, Heft 7.

NAASRA (1987). Pavement Design. A Guide to the Structural Design of Road Pavements.

NESNAS K and MERRILL D (2002). Development of Advanced Models for the Understanding of Deterioration in Long-Life Pavements. BCRA Workshop on Modelling of Flexible Pavements, Lisbon.

OECD (1998). Dynamic interaction between vehicles and infrastructure experiment (DIVINE), Technical Report DSTI/DOT/RTR/IR6(98)1/FINAL.

PATTERSON WDO (1985). Prediction of Road Deterioration and Maintenance Effects: Theory and Quantification, Vol. III, Transport Department, World Bank, Washington, D.C.

ROAD RESEARCH LABORATORY (1970). A guide to the structural design of pavements for new roads. Road Note 29, Third Edition. London: HMSO.

ROBINSON RG (1988). Trends in axle loading and their effects on design of road pavements. Research Report 138. Crowthorne: Transport and Road Research Laboratory.

SMITH HA (1991). Truck tire characteristics and asphalt concrete pavement rutting. Transport Research Record 1307, TRB, Washington: National Research Council.

TRANSIT (2000). New Zealand supplement to the document Pavement Design - A guide to the structural design of road pavements AUSTROADS (1992). Transit New Zealand, Wellington, New Zealand.

TROTT JJ and GRAINGER JW (1968). Design of a dynamic weighbridge for recording vehicle wheel loads. Road Research Laboratory Report LR 219. Crowthorne: Road Research Laboratory.

Appendix A. Assessment of data sources

Three sources of information on vehicle loads have been identified (WIM data, ‘static’ surveys and CSRGT). The advantages and disadvantages of each are examined in this Appendix.

A.1 WIM (Weigh-In-Motion)

Weigh-In-Motion devices are located in the road surface and give a measure of the instantaneous axle loads of vehicles travelling at normal traffic speeds.

Advantages of WIM

- WIM devices give a continuous measure of traffic loading
- WIM devices provide information on actual instantaneous axle loading
- WIM devices provide a large amount of data and hence can be good value

Disadvantages of WIM

- WIM systems have been installed at a relatively small number of fixed locations and therefore only provide a small sample of traffic
- WIM devices measure a dynamic load that is influenced by the interaction between the vehicles and the road profile. This affects the accuracy of the measurements. In addition, they do not necessarily measure the true dynamic load as they are normally calibrated using the static loads of a limited number of calibration vehicles. The accuracy can also be influenced by the type of sensor and how the data are processed
- Vehicles are usually classified on the basis of their dimensions. There may be errors in classifying vehicles

Errors associated with WIM devices and their effect on traffic and pavement design.

Hakim and Thom (1998) determined two different types of error associated with WIM devices: calibration errors and measurement errors. In order to explore the interaction of these errors, three scenarios were tested.

- Only measurement error
- Measurement and calibration error
- Measurement and calibration error with a shift associated with one type of device

They found that the ‘measurement error only’ scenario resulted in an error in the 20 year traffic prediction of between 5 and 15% (using a 4^{th} power). The ‘measurement and calibration error’ scenario produced traffic prediction errors of between 15% and 20%. These error estimates increase with the exponent of the power law. Larger errors may occur when less random errors are taken into account; traffic prediction errors of up to 50% were stated in this case.

Frith and Barbour (1992) compared wear factors produced using WIM systems with those produced for the same vehicles using data from enforcement weighbridges. The ratio was very variable between sites (between 0.67 and 2.06).

A.2 'Static' Surveys

During static surveys, goods vehicles are chosen at random from the traffic flow and the loads applied by each axle are measured using slow-speed dynamic axle weighers or portable weighpads.

Advantages of static surveys

- Static surveys can provide detailed information about the vehicle such as the vehicle type, axle loads, tyre types, suspensions, the purpose of journey, etc
- The axle and vehicle weights are normally accurate to within about 100 kg per axle

Disadvantages of static surveys

- There is risk of bias. Overloaded vehicles may try to avoid the survey site through fear of prosecution
- Static surveys are expensive to perform - in addition to the equipment and staff required to measure loads, traffic management and the assistance of the police is necessary
- They provide data about a relatively small number of vehicles

Errors associated with Static Surveys

Although the devices used in static surveys have the same type of errors as WIM devices (measurement and calibration errors), these errors are much smaller. There are sampling errors due to the relatively small sample of traffic and possible bias due to drivers avoiding the site.

A.3 CSRGT (The Continuing Survey of Road Goods Transport)

The Continuing Survey of Roads Goods Transport (CSRGT) is a database of road goods transport maintained by the Department for Transport from which annual statistics are produced. The survey is conducted using a postal questionnaire that covers vehicle movements and loads carried.

Advantages of using the CSRGT

- CSRGT provides a historical record of HGV use and therefore enables trends in use to be examined
- Data from the CSRGT is freely available to the Highways Agency
- CSRGT records detailed information about the vehicles sampled and their use on a typical week including vehicle type, distances travelled and loads carried
- CSRGT contains a significant sample of the heavy vehicle fleet
- The detailed information enables trends to be explained, for example changes in vehicle weights can be related to commodities carried

Disadvantages of using the CSRGT

- CSRGT only contains information on UK registered vehicles - it does not include foreign registered vehicles
- Although completing the postal questionnaire is a statutory requirement, there is a degree of trust regarding the accuracy of the information provided
- CSRGT cannot provide information about individual axle weights and the Gross Vehicle Weights in the survey are often estimated by the operators (they may be reluctant to report overloading)

Errors associated with the CSRGT

CSRGT sampling errors are relatively small. However, additional errors are introduced when estimating wear factors. This process involves using CSRGT data to estimate vehicle travel by degree of lading for each of the main classes of vehicle, and then to allocate axle loads or wear factors to this lading pattern.

A.4 Recommended data sources

The primary data required are axle weights and vehicle types. Additional detailed information (including the tyre, suspension and axle types) may be required for detailed analysis (for example, using the Eisenmann equation). Trend information is useful to aid projections about future goods vehicle use.

It is recommended that vehicle wear factors are based on WIM data, with CSRGT data used to examine trends in vehicle use and occasional ‘static’ surveys conducted to examine trends in other factors (such as tyre, suspension and axle types).

Appendix B. Derivation of Vehicle Wear Factor from WIM devices

Twelve WIM sites were used in the analysis. These were on both carriageways at:

- M4 (Junction 15-16)
- M6 (Junction 2-3)
- M20 (Junction 10-11)
- M25 (Junction 29-30)
- M40 (Junction 15-16)
- A1(M) (Sawtry)

The A1(M) at Sawtry was a 4-lane dual carriageway, the other sites had 3 lanes in each direction. WIM devices were located in lanes 1 and 2, except at the M4 and M40 where they are only in lane 1. The measurements from four WIM sites covered January to October 2003, the measurements at other sites covered a period from July to October 2003.

B.1 Filtering

The raw WIM data was filtered to increase the speed and reliability of the analysis.

To remove light vehicles, a minimum unladen weight was defined for each vehicle class and vehicles weighing less than 80% of these values were rejected. Cars were removed from the data by excluding vehicles with axle spacing less than 3m.

Vehicles that were unrealistically heavy were also removed. They were rejected that had either a total weight or axle weights 50% greater than the legal maximum.

Filtering reduced the number of vehicles by approximately 70%.

B.2 Calculation

Each data set contained measurements for one calendar month and these were the analysed using a custom-written computer program which calculated wear factors (using the fourth power law) and percentiles. The following output statistics were saved for each vehicle class:

- Mean wear factor
- Median or 50th percentile wear factor
- 75th percentile wear factor
- 85th percentile wear factor
- 90th percentile wear factor
- 95th percentile wear factor
- Total number of vehicles

The proportion of vehicles travelling in each lane was also output.

Summary statistics were then produced for each site. At this stage, it was possible to detect data sets that had unusual values, including very high or very low mean wear factors and unusually low vehicle counts (these may indicate road works or another disturbance that could affect the vehicles using the road). Some of these data sets were excluded from the analysis.

The wear factors obtained for each site were then used to calculate the overall average wear factors for each vehicle class (weighting each wear factor by the number of vehicles analysed in each class at each site).