European Co-operation in the Field of Scientific and
Technical Research

COST 334

Effects of Wide Single Tyres and Dual Tyres

Final Report of the Action

European Commission
Directorate General Transport

version 29 November 2001 Taskgroup 3 Final Report

Legal notice

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Table of Contents

Chapter 4 : Pavement Wear Effects (TG3)

4.1 INTRODUCTION

Wide single tyres, as an alternative to dual tyres, can provide cost savings to the road freight transportation industry through reduced tare weights, fuel consumption and tyre wear. However, wide single tyres are often stated to produce more pavement wear than dual tyres, for the same axle load. Quantification of this allegedly increased pavement wear of wide single tyres, relative to dual tyres, is necessary in order to seek a balance between increased savings to the transport industry, and increased costs to road owners.. This could provide a basis for appropriate regulatory or legal actions such as differential load limits, differential vehicle taxing or tyre pressure limits.

Within the framework of COST 334, Task Group 3 was specifically devoted to the determination of the relative effects of single tyres, wide base single tyres and dual tyres on the wear of pavement structures. Section 4.2 presents the scope and limitations of the work executed by Task Group 3.

It should be stressed that the effects of different tyres on pavement wear are only partly (if at all) caused by the differences in the tyre type as such. Many effects of different tyres are related to differences between those tyres in their loading capacity, recommended inflation pressure and tyre – pavement contact area. In the eighties, for example, dual tyres operating at an inflation pressure of about 7 to 8 bar were often replaced on trailers and semitrailers by wide base singles mostly operating at a pressure of about 8 to 9 bar for the same axle load. Any resulting differences in pavement wear are partly caused by the pressure differences, and partly by the difference in tyre type (dual tyres spreading the load over a wider area than wide base singles), depending on distress mode and pavement type. In present practice (2000 A.D.), many wide base single tyres still have higher inflation pressures than dual tyres, at the same loading capacity. However, modern tyre types may be inflated up to 9 bar, both single and dual, suppressing the inflation pressure difference. Similar considerations apply to axle loads, where different tyres or tyre types can accommodate different axle loads.

Figure 4.1 - Examples of dual tyre assembly and wide base single tyre

The OECD (1983, 1988) has previously stated that an axle with wide base single tyres inflicts about equal pavement damage as two (1.2^4) axles with dual tyres and the same axle load. However, this figure may well have changed since its publication, because of changes in tyres and loading conditions, amongst other things. There is also considerable doubt as to the general applicability of this figure, because the effects of different tyres and loading conditions are often dissimilar for different pavement types/thicknesses and also depend on the type of pavement wear (distress). Therefore, it was necessary to concentrate the basic question on those tyre types, loading conditions, pavement structures and types of pavement wear, that are most relevant for European present-day practice.

Similarly, several methods exist to assess the effects of tyre loading on pavement wear, and to quantify the results. These methods each have their advantages and disadvantages, and not all of their results can be easily combined. Therefore, the available methods had to be described and a selection agreed upon.

An inventory of the most relevant combinations of cases and a description of the chosen research methods and quantification format is given in section 4.3, ending with the technical issues that remained to be answered by Task Group 3.

These issues, expressed as questions, are treated in sections 4.4 to 4.7, drawing both on literature of previous research and on the new research executed within the framework of Task Group 3. The answers to the questions are combined in section 4.8.

The conclusions and recommendations stemming from these efforts are given in section 4.10. Sections 4.10 and 4.11 present a glossary of technical terms and abbreviations, and the referenced literature

4.2 SCOPE OF THE WORK

Historically, a great deal of research work has been carried out on the relative damaging effects of different wheel loads on road pavements. However, because it was not of interest at the time (~1960), much of this work was carried out without regard to the effect of tyre type or size. Generally, the results of this work have shown that, with few exceptions, the relative damaging effect of wheel loads on pavements can be described by the "Fourth Power Law". Although some departures from this rule have been noted, it continues to be the most widely used basis for pavement design purposes, and is not the subject of the investigations undertaken by Task Group 3 (TG3).

More recently, the effects of other vehicle-related parameters on pavement damage have been investigated, notably the vehicle suspension characteristics and the tyre type. In the past 10-15 years, many researchers have investigated the effect of tyre type by examining the relative effects of, for example, the use of wide single tyres and dual tyres. Generally, these investigations have focused on the most commonly used wide single tyre (385R65/22.5), which have been compared with the dual tyre type prevailing at the time. The latter has varied from country to country, but has been generally of the 10R20, 11R20, 11R22.5, or 295R80/22.5 type.

In the last 5 years, however, the range of both wide single tyres and dual tyres has increased substantially. Wide single tyres are available also in 425 and 445 section widths, with prototype tyres now also available in 495 mm section width. At the same time, dual tyres are now available in section widths of 315mm, with aspect ratios (height over width) of 60, 70 and 80%. In these circumstances, the effect of tyre type on pavement damage may be more complex than originally thought.

The principal objective of TG3 was therefore to determine quantitatively the relative effects, for the same axle load, of these different modern tyre types on the wear of pavement structures.

As a first step, TG3 decided to identify the most relevant (i.e. most common) conditions of tyre – pavement interaction to focus its study upon. This requirement was condensed into the following preliminary research questions:

1. What are the general characteristics of truck traffic in Europe, regarding: vehicle type, number of axles, axle and wheel loads?
2. What are the pavement types that are relevant for the European situation and what are the relevant distress modes for the different climates and pavement structures?
3. What are the stresses in the tyre - pavement interface?

Secondly, the methods to assess the effects of tyre loading on pavement wear, and to quantify the results were identified, by addressing the following questions:

4. Which methods can be used to determine the effects of tyres on pavement wear (performance)? This includes also the question how to extrapolate the effect on pavement response to the effect on wear of pavements.
5. Which methods can be used to describe the effects of tyres on pavement wear in such a way that it is easy to understand, to present and to use in quantitative studies for e.g. cost analysis?

The results from these inventories are presented in section 4.3. On completion and consideration of these inventories, it was felt that the main research questions left to be resolved could be divided into three groups:

- information on tyre parameters for purpose of analysis and interpretation of the results (see section 4.4),
- the behaviour of the tyre - pavement interaction under controlled conditions(see section 4.1),
- the translation of the previous behaviour to real world conditions (see sections 4.6 and 4.7).

Even after focussing on the most relevant tyre types, loading conditions, pavement structures and distress mechanisms, a large number of combinations remained to be investigated. Due to time and cost limitations, only a number of combinations was investigated in depth. Results for other combinations were extrapolated from these findings, on bases that are described later. It should be noted that even the results of the in-depth investigations are subject to the limitations of the available research methods (see section 4.3.7).

4.3 DEFINITION OF THE PROBLEM

4.3.1 Introduction

This chapter presents the answers to the preliminary research questions noted in the previous section. These concern:

- the general characteristics of truck traffic in Europe (section 4.3.2)
- the relevant pavement types for the European situation (section 0)
- the stresses in the tyre - pavement interface (section 4.3.4)
- the relevant distress modes for the different climates and pavement structures present in Europe (section 4.3.5)
- available methods to determine the effects of tyre types on pavement wear (section 4.3.7)
- available methods to quantitatively describe the effects of tyres on pavement wear (section 0)

4.3.2 General characteristics of truck traffic, trucks, axles and tyres

4.3.2.1 European requirements for Gross Vehicle Weight and axle weights

Within the European Union (EU) the maximum gross weight and the maximum axle weights for trucks and units have been harmonised for vehicles on an international journey - these limits are contained in Directive 96/53/EC (EU 1996). Member states are still free to set national weight limits, which may be higher or lower than those within the Directive, but must accept vehicles that comply with the Directive.

The maximum gross weight for an articulated vehicle and truck-trailer combination on five or more axles has been harmonised at 40 t. However, to encourage intermodality, certain articulated vehicles operating in combined transport modes, and having five or six axles, can operate at 44 t. (It should be noted in this context that in two northern countries of Europe, Sweden and Finland, domestic regulations allow Gross Vehicle Weights up to 60 t (Henriksson 1998)).

The maximum gross weights for some vehicles are also dependent on the type of tyre arrangement and suspension fitted. For example, the maximum gross vehicle weight of a three axle rigid vehicle is one tonne higher (26 t as opposed to 25 t) if twin tyres and road friendly suspensions are fitted or no drive axle exceeds 9.5 t. In a similar manner a four axle articulated vehicle is limited to 36 t, as opposed to 38 t, unless dual tyres and road friendly suspensions are fitted to the drive axle.

Maximum axle weights have been harmonised at 10 t for a single non-driven axle. Although some single trailer axles would be used at this weight, steering axles are usually operated at 6 t – 7 t. The maximum for a single drive axle is 11.5 t. The maximum load for a tandem drive axle is 18 tonnes, when the axle distance is between 1.3 and 1.8 m, except with dual tyres and road friendly suspension for which it is raised to 19 tonnes. Road friendly suspension is defined as air suspension or other equivalent that meets the technical specification in Annex II of the Directive 96/53/EC.

In order to obtain a sufficiently accurate picture of the European situation, TG3 undertook a survey of goods vehicle data in several European countries. The survey was based on published national data, supplemented by other data obtained from reputable sources. The results of these surveys assisted in setting the conditions for further experimental work undertaken by COST 334, and contributed to the identification of future trends in vehicle and tyre design and operation. The following sections present a synthesis of the results of these surveys, which are described more fully elsewhere.

4.3.2.2 European vehicle types and number of axles

The truck population in different European countries varies considerably. Traffic counting in different countries (DE, NL, AT, IT, FR, SL, UK, NO, FI) leads to the conclusion that (except in the cases of NO and FI) the proportion of tractor-semitrailer units is about 50%. In NO, UK, and FR the share of single trucks is higher (40%-60%) than for the other countries (20%-35%). FR and UK have a much smaller proportion of truck-trailer units (5%) compared to the other countries (20%-35%). Finland has about 25% single trucks, 19% tractor-semitrailers and 56% truck-trailer units. (Molzer et al 1995, Vos 1996, Werner 1997, Dept. transp. 1997, Henriksson 1998, ZAG 1998, Refsdal 1998, Huhtala 2000b). Terms like ‘truck’, ‘trailer’, ‘tractor’, ‘semitrailer’, etc. are explained in the glossary (section 4.10).

The number of axles per vehicle is dependent on the maximum Gross Vehicle Weight allowed. By correlating the national data with relevant changes in national legislation, it can also be concluded that such changes in legislation, concerning Gross Vehicle Weight, cause the truck fleet to change rapidly (Mitschke 1985, Glaeser 1997).

Counts of different axle combinations and configurations from the NL, AT, FR, UK, NO and DE are summarised in Figure 4.2 (Molzer et al 1995, Vos 1996, Glaeser 1997, Penant 1997, Addis 1998, Refsdal 1998). Because of the different counting conditions (motorway network or highways, and different definitions of trucks due to Gross Vehicle Weight) the figures are not directly comparable. However, they are sufficiently comparable to give an overall picture of the European situation in respect of truck types used. Note that in Sweden and Finland the axle combination 3-axle truck with 4-axle trailer is very common (Henriksson 1998).

If a truck or a tractor has two rear axles, the rearmost axle is in most cases a towed axle, rather than a driven axle. In Finland, Sweden and some other countries it often can be lifted up when the truck is empty.

4.3.2.3 Vehicle loading conditions

The overall loading situation can be described as follows. Of about 5 million truck journeys in 1995 in Germany, 44% were empty journeys. In long distance heavy goods transport the proportion of empty rides is lower, and can be estimated at 30%. The proportion of empty rides in transit traffic is much lower, at only 7% (Deutscher Bundestag 1997) It is anticipated that better communication systems and other technological advances will decrease these proportions of empty rides in future.

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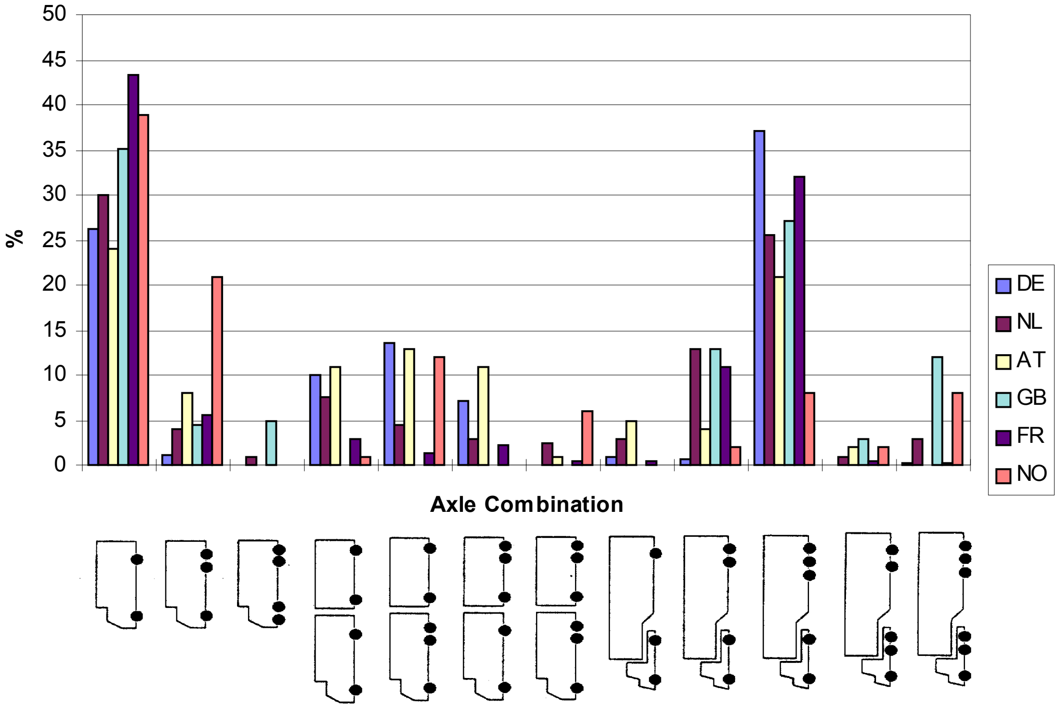


Figure 4.2 - Axle combinations from traffic countings in different European countries

Overloading of truck, truck-trailer, and tractor-semitrailer-units can be observed in 10-15% of the cases on German highways (Werner 1997). For the Netherlands a figure of 10% of the truck and trailer axles exceeding an axle load of 10 t and 0.5% exceeding 15 t is given by Vos (1996). Overloading is a special problem in the transport of fluids, bulk materials and wood. Molzer et al. (1995) mention a figure of 60% of overloaded trucks in bulk goods transport for Austria with the note that these trucks mainly travel short distances (mainly site traffic). Non-bulk goods in long distance transport tend not to reach the load capacity of the truck, and average only about 70% of capacity (Dettweiler et al. 1999).

4.3.2.4 Axle loads and wheel loads

Axle loads for 40 t Gross Vehicle Weight truck-trailer and tractor-semitrailer combinations are:

- 6-7 t for the steering axle,
- up to 11.5 t for the drive axle,
- up to 8 t for each towed (trailer or semitrailer) axle.

Results of axle load measurements for a standard 40 t tractor-semitrailer combination in DE are shown in Figure 4.3. Overloading for this type occurs in about 20% of the cases.

Overloading (more than 5%) of the complete truck or unit can be estimated to occur in

10%-15% of all journeys (Glaeser 1998). Most often the drive axle of the towing vehicle in a tractor-semitrailer unit is overloaded, because the payload is placed farthest forward on the semitrailer for security reasons, (emergency breaking or accident).

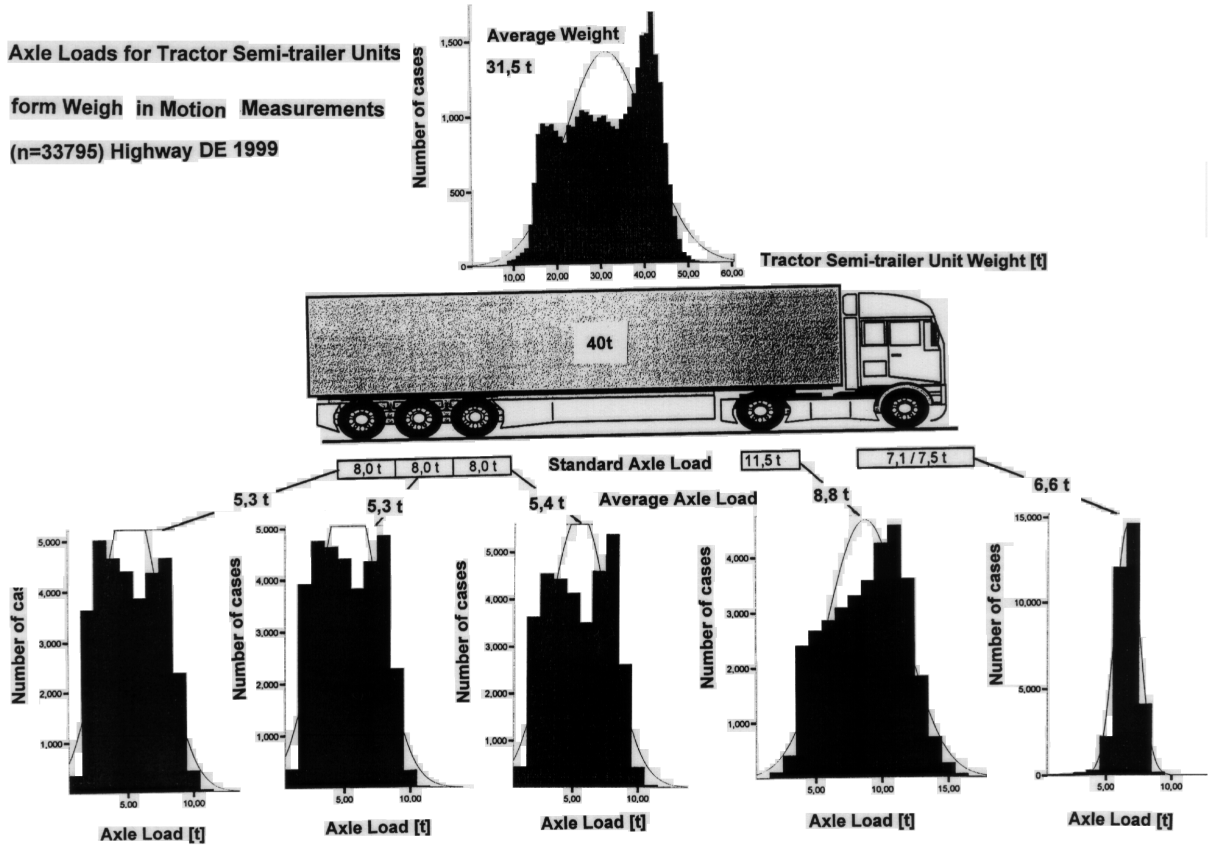


Figure 4.3 - Axle loads for tractor-semitrailer units from weigh-in-motion measurements (n=33795) highway DE 1999 (Alsfeld)

4.3.2.5 Tyre sizes

Tyre sizes are coded as e.g. 12-22.5, 12R22.5 or 425/65R22.5, where:

12 = nominal section width code (S in Figure 4.4)

425 = nominal section width in mm (S in Figure 4.4)

/65 = tyre aspect (height to width) ratio in percent (H/S in Figure 4.4)

\- = construction code; indication for bias or cross ply tyre structure (nowadays mainly obsolete)

R = construction code; indication for radial ply tyre structure

22.5 = the nominal ‘rim diameter’ expressed with a code, where the decimal point identifies the tyre to rim fitment configuration (15° tapered bead seat rims) (∅ in Figure 4.4).

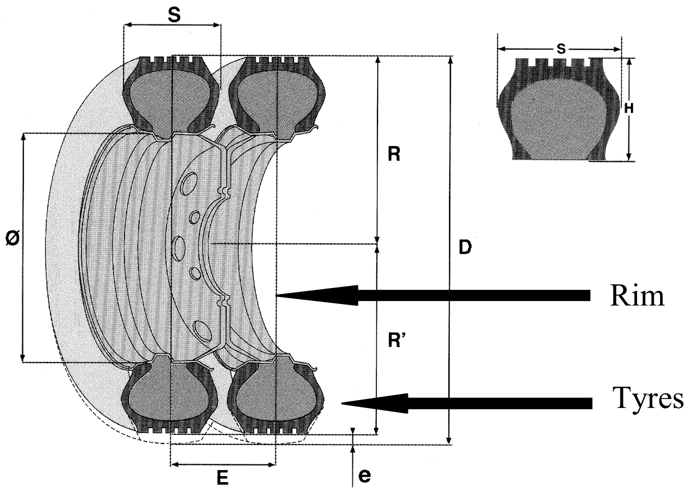


Figure 4.4 – Tyre size parameters

It should be noted that the tread width of a tyre is less than the section width. This fact is important, as the impact of the tyre to the pavement is generally accepted to be determined by the footprint width and not by the nominal section width. For radial tyres, the footprint width of a tyre generally equals the tread width (except for strongly over-inflated or 'under-loaded' conditions when the footprint width may be less). Similarly, the outer diameter of the tyre is not only determined by its rim diameter, but also by its sidewall height, indicated by its aspect ratio and width. This too is important, since the outer tyre diameter is one of the factors influencing the footprint length, together with the wheel load and inflation pressure.

Different tyre sizes and dimensions can be found on different axles of trucks and tractors on the one hand and trailers and semitrailers on the other hand. Tyre sizes in use were examined by analysing the reports of tyre changes on site in Germany (n=7347) (Glaeser 1997b) The following data were drawn from this research. (Note that the situation outside Germany may be different.)

- On trucks and tractors the tyre sizes 315/80R22.5 and 295/80R22.5 have nearly the same share (23% and 27% respectively, noting that in 17% of all cases the tyre size is unknown).
- On front axles of trucks and tractors one can find an increasing number of wide base single tyres (385/65R22.5). At present, about 4% are wide base singles on the front axles in Germany, whereas in Norway this figure rises to about 23%.
- On trailers and semitrailers the tyre size 385/65R22.5 has a share of 45% and the tyre size 365/80R20 has a share of 20% (assuming that also 17% of the trailer tyres sizes are unknown). The tyre size 425/65R22.5 has a share of only 1%. All these tyres are of course mounted on trailers and semitrailers as single tyres.
- In 11% of the cases the tyre size is smaller than 22.5. The tyre size 275/70R22.5 has a share of 5%, all other 22.5 tyre sizes together have a share of 20%.
- Smaller tyre diameters, mounted as twins (e.g. on volume trucks and trailers), have the following share: 17.5 tyres 9% and 19.5 tyres 4%. Other twin mounted 22.5 trailer tyres have a share of about 4%.
- About 50% of all tyres on heavy vehicles are retreaded tyres.

- Tyre defects happen more often on trailers and semitrailers than expected from axle countings (and sales figures) of new tyres:

(Germany 1997)	Tyres „on the Road“	Tyre Defects
Truck or Tractor Steering Axle	17%	14%
Truck or Tractor Drive Axle	37%	23%
Truck or Tractor Trailing Axle	4%	4%
Trailer or Semitrailer Axle	42%	59%

4.3.2.6 Future trends

COST 334 has been particularly concerned to identify future trends in tyre development and use in Europe. In this way, methods can be developed not only for assessing current tyre types but also future tyre types. The approach used by COST 334 has been to take advice from tyre and vehicle manufacturers on likely future trends, and to build these into the requirements for other parts of the work done by COST 334.

At this stage, it is useful to summarise the likely future trends that can be foreseen. On the basis of the advice given to COST 334, it is likely that:

- There will be a further change from 2 axle truck + 2 axle trailer and 2 axle truck + 3 axle trailer to the combination 3 axle truck + 2 axle trailer. The benefit of such a trend is that it will allow the transport of the same container sizes on truck and trailer, for combined traffic purposes.
- The combination of 2 axle tractor + 3 axle semitrailer will continue be the most popular unit in heavy goods transport (today and in future), except in the case of NO, FI, SE and UK, where the 3 axle tractor is already, and will remain, in common use.
- There will be more purpose-built trucks and units for special transport tasks in the future.
- Increasing load volumes (while maintaining existing restrictions on overall dimensions) of trucks and units will be achieved by lowering the kingpin height and by lowering the height/width ratios of tyres.
- A further trend away from the use of leaf springs on rear truck and tractor axles and on trailer and semitrailer axles, to be replaced by air springs can be expected. Steering axles of trucks and tractors will continue to be equipped with leaf springs. In the longer term, trucks will be equipped with electronic devices for tuning spring and damper rate – the so-called “active suspension”.
- Current popular tyre sizes for heavy goods units are 385/65R22.5 and 365/80R20 for trailer and semitrailer axles and 315/80R22.5 and 295/80R22.5. For truck and tractor steering and power axles, there is a likely trend towards the use of smaller height-width ratios (70% or 60%).
- A future trend to mount wide base singles (385 section width) on the steering axles of trucks and tractors can be expected. These will provide longer tyre life and better truck appearance for the same cost as at present.
- The drive axle(s) of heavy goods vehicles will possibly be equipped with wide base single tyres, such as 495/45R22.5.
- The use of alloy rims to save tare weight will increase.

- Trucks may travel increasingly without spare wheels to save weight. This will require greater tyre reliability and better tyre repair service on site, and may therefore not apply to less densely trafficked areas.

Figure 4.5 shows the tyre situation in the past, in the present and (possibly) in the future, as example for a heavy goods tractor-semitrailer combination.

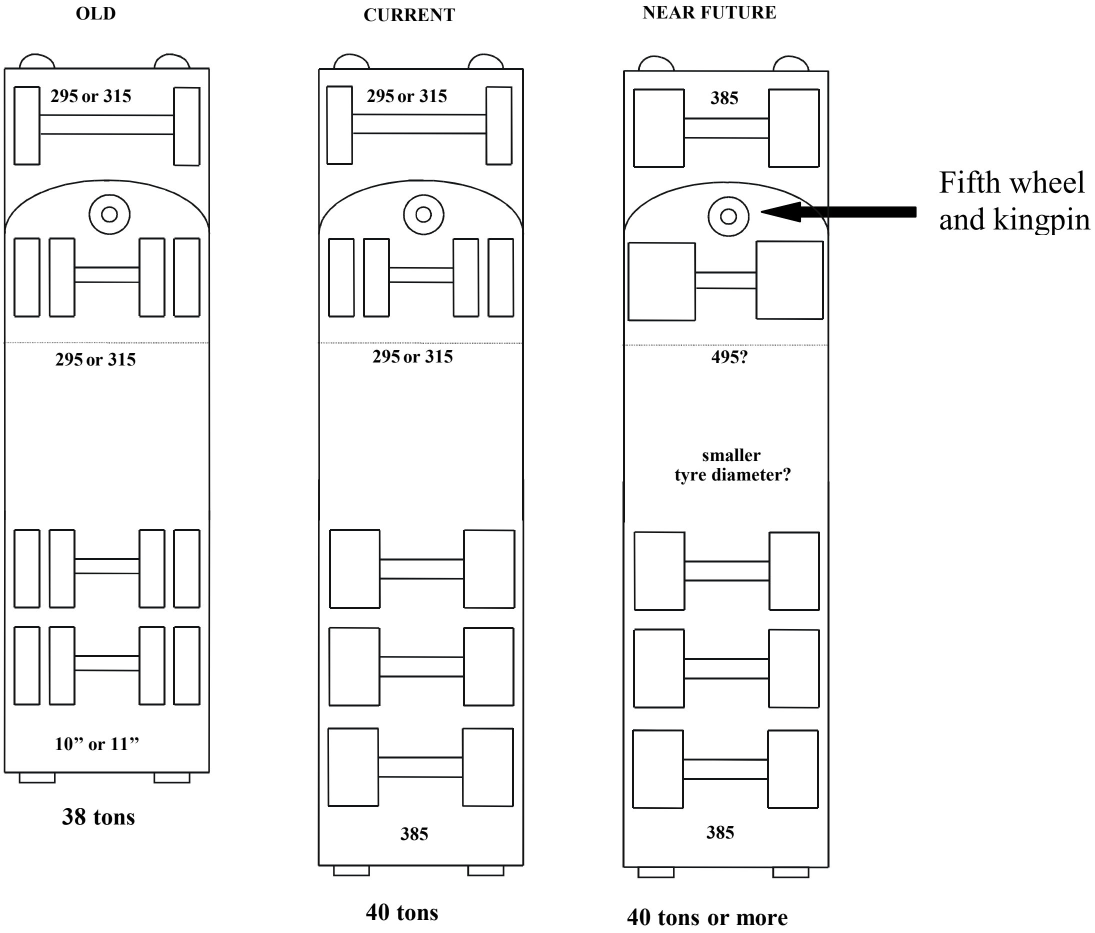


Figure 4.5 - Tyres of articulated vehicles in the past, present and (possibly) future

4.3.3 Pavement types in Europe

4.3.3.1 Introduction

What are the pavement types that are relevant for the European situation, and what are the distress modes for the different climates?

In order to examine this question in the context of the effects of the use of different tyre types, it is first necessary to identify the extent of the European road network that might be affected by the choice of different tyres, and the mechanisms by which such roads deteriorate. In order to do this, the work of COST 334 can draw heavily on work already completed by COST 333 (1997). This latter group has examined the question in some detail, and what follows in this section is largely extracted from their work.

4.3.3.2 *Road lengths*

In considering the pavement types relevant to Europe, it is first necessary to recognise that in most EU countries there exist at least two levels of road network, and that there are also three general types of pavement construction.

In general, each EU country has a national road network comprising the major roads (motorways and the principal non-motorway routes), together with the "local" road network. Again, in general terms, it is probably the case that the national road network, although more limited in total length, carries the majority of heavy commercial vehicle traffic. Table 4.1 illustrates the extent of the road network in each of the EU and EFTA (European Free Trade Association) countries.

Table 4.1 - Length of road by country (thousand kilometres) (DETR 1999)

Country	All roads	Of which motorways	All roads per 1000 km2
Austria	106	1.6	1.267
Belgium	143	1.7	4.698
Denmark	71	0.8	1.654
Finland	78	0.4	0.231
France	916	8	1.675
Germany	641	11.3	1.796
Greece	116	0.2	0.879
Irish Republic	92	0.1	1.302
Italy	816	6.4	2.709
Luxembourg	5	0.1	2.032
Netherlands	104	2.2	2.541
Norway	91	0.1	0.281
Portugal	72	0.6	0.784
Spain	160	7.5	0.317
Sweden	135	1.1	0.300
Switzerland	71	1.6	1.720
United Kingdom	389	3.3	1.594
Total	4006	46.8	

From the point of view of the objectives of COST 334, it is likely to be the motorway network that carries the greatest volume and weight of traffic as heavy goods vehicles. This does not mean, however, that the remainder of the network can be ignored. In the UK, for example, it is estimated that motorways, together with the principal roads in the remainder of the network, amount to about 5% of all roads. This is illustrated in Table 4.2, which gives further information for each EU country, and others.

Table 4.2 - Length of Primary Road Network in European Countries (COST 333)

Country	Proportion of construction types (%)			Length of primary road network (km)
	Flexible	Composite	Rigid	
Austria	90	5	5	12,000
Belgium	70	13	17	15,700
Croatia	94	5	1	7,000
Denmark	98	2	0	7,000
Finland	95	5	0	13,400
France	50	40	10	36,300
Germany	36	36	28	52,900
Greece	100	0	0	12,000
Hungary	60	40	0	6,800
Iceland	99	1	0	4,300
Ireland	100	0	0	2,700
Italy	-	-	-	6,500
Netherlands	86	10	4	2,200
Norway	98	0	2	-
Poland	-	-	-	45,600
Portugal	85	5	10	10,000
Romania	80	15	5	-
Slovenia	95	0	5	4,700
Spain	79	17	4	24,100
Sweden	99	<1	<1	15,000
Switzerland	75	3	22	1,500
UK	85	5	10	18,800

On the basis of the information given in Table 4.2, it is clear that flexible road constructions tend to be the predominant type used in European countries, as is illustrated in Figure 4.6.

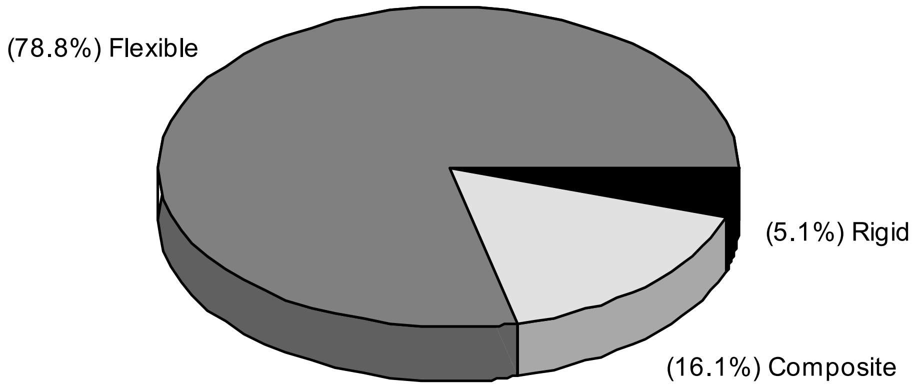


Figure 4.6 - Proportion of types of construction for new roads

Heavy goods transport takes place mainly on highways and national roads. In Germany, for example, 72% of road freight is transported on the primary road network (BMV 1995). In the UK, the primary route network carries some 55% of the total freight (tonne-km) occurring. On the assumption that the situation is similar in most other countries, then it is both the motorway network, and the local road network whose pavement constructions are of interest.

4.3.3.3 Modes of pavement deterioration in relation to tyre type

The significance of the different pavement construction types is that each will have different modes of distress and failure. It is common, for example, that bituminous roads deteriorate and fail by rutting in the wheel paths, that composite pavements deteriorate through excessive cracking and rutting, and that fully cemented pavements also fail (over a longer period) by cracking or slab movement.

Fortunately, most of the experimental evidence available on the distress caused by different tyre types refers to the fully flexible pavement, as this is the more usual type of pavement in use in Europe.

Although, in Europe, detailed pavement design methods for flexible construction vary, as has been established by the work of COST 333, the principles employed remain the same. A pavement is designed to carry certain, estimated, levels of traffic for a specific period known as the pavement life. In some countries, the methods used are mechanistic, in which the mechanical properties of the materials of construction are measured, and used in a systematic design equation, whilst in others, a more empirical approach is used. A mixture of these two approaches is also used.

4.3.3.4 Common pavement structures

In order to assist the experimental work undertaken by COST 334, it was desirable to identify a limited number of designs representative of those used throughout Europe. These will form the basis of experimental work to be carried out, and will also be used as the typical pavement in calculations of overall costs and benefits.

The selection of pavement designs is difficult, because of the wide range of designs used for specific traffic levels. Some simplified approach was necessary, and this was based on the analysis of pavement designs carried out by COST 333.

Each country participating in the questionnaire prepared by COST 333 was asked to give examples of the most commonly used pavement designs for cumulative traffic levels of 1, 10 and 100 million standard (80 kN) axles (msa) and a subgrade CBR of 5 per cent. As an example, the design thicknesses for 10 msa are illustrated in Figure 4.7.

To enable these designs to be broadly compared, each was converted to an equivalent thickness of bituminous material. Using widely accepted equivalence factors, 100 mm of untreated granular material was assumed to be structurally equivalent to 30 mm of bituminous material. The equivalence between the thickness of asphalt and untreated granular material is only an approximation. Some countries use a very thick granular layer as a non-structural layer to protect the subgrade from frost. In such cases, where very thick granular layers are used, the equivalent thickness will be unrealistically large, and the equivalence will depend on the stiffness of the asphalt, which in turn will largely depend on the penetration grade of the binder used. For this reason, the penetration of the binder used in the main structural layer of the road is given, where known, above the design thicknesses in Figure 4.7. The equivalent thicknesses are shown above the corresponding design for each country and the design thicknesses are summarised in Table 4.3. It should be noted that not all countries have a requirement to design roads for traffic levels as high as 100 msa.

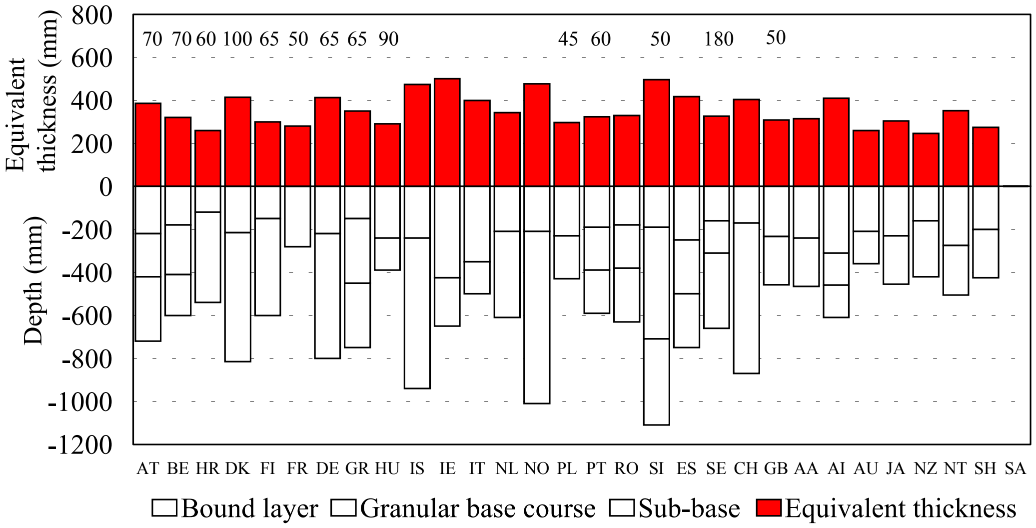


Figure 4.7 - Designs for cumulative traffic of 10 msa

Table 4.3 - Summary of designs (Nunn et al. 1997)

		Cumulative Traffic		
		1 msa	10 msa	100 msa
Equivalent thickness (mm)	Mean	273	378	436
	Thickest	383	497	527
	Thinnest	183	280	330
Thickness of asphalt (mm)	Mean	119	218	295
	Thickest	300	425	410
	Thinnest	25	150	230
Total thickness of pavement (mm)	Mean	573	689	711
	Thickest	1030	1110	1050
	Thinnest	210	280	330

4.3.3.5 Recommended thicknesses of pavements for use in COST 334

The data given in Table 4.3 shows a wide range of thicknesses for a given application, and there is also a substantial anomaly in the thickest asphalt layers for the 10 msa and 100 msa design requirement. This is due to the differing requirements for foundation thickness in different countries.

For the purposes of the work carried out in COST 334, and in particular for the programme of experimental work, it was thus necessary to examine the effects of tyre type on all types of flexible pavement. All design traffic levels needed to be covered, in order to recognise the different traffic conditions from country to country. Taking the mean values of thickness of asphalt layer gives a range of 119 - 295 mm for the three traffic levels.

The difficulties of covering this wide range of thicknesses in any experimental work are clear, and it was therefore proposed that typical thicknesses within the range of interest should be selected. Given that the maximum and minimum thicknesses of pavement design for a particular traffic level are very different, it was proposed that the following thicknesses of asphalt pavement construction be used as typical examples of European practice.

Table 4.4 - Recommended thicknesses of pavement construction for COST 334 experimental work

	Traffic level 5msa	Traffic level 10msa	Traffic level 100msa
Pavement thickness (asphalt construction)	75-100 mm	180-200mm	300-350mm

4.3.3.6 Recommended materials characteristics of pavements for use in COST 334

In addition to a wide range of pavement thicknesses for a given service level of traffic, European pavement construction employs a wide range of material types, leading to a variability of pavement strengths. In considering a possible experimental programme to study the pavement wear effects of wide single and dual tyres, therefore, it was necessary to take into account, as far as possible, such variations.

For the purposes of the experimental programme, it was necessary to construct typical examples of pavements designed for an appropriate service level of traffic, and to use materials in their construction that were again representative of those used in Europe. The mechanical properties of a wide range of European materials were reported by COST 336 (1999). On the basis of the above information, it was possible to suggest typical values for use by COST 334, which were the target values to be achieved in constructing experimental pavements. However, it was not possible to take into account all of the factors that may affect the elastic properties of the material, such as temperature, laying conditions etc.. It was therefore proposed that values were adopted that represent typical materials in the range that might be encountered, and the values in Table 4.5 were suggested.

Table 4.5 - Recommended target values for elastic characteristics of pavement materials for COST 334 experimental work

	Bituminous material	Cemented materials	Granular material	Subgrade
Stiffness (MPa)	5000 – 7500	10000 – 15000	300 – 500	30 – 50
Poisson’s Ratio	0.4	0.2	0.3	0.2 – 0.4

4.3.3.7 Other factors

There is some, limited, evidence to suggest that pavement thickness may be important in determining the nature of the response of a pavement to a given load. Huhtala et al (1997) considered the response of two thicknesses of pavement to a dynamically applied load. They observed that for a medium pavement (150 mm bituminous thickness) the strain at the bottom of the bituminous layer was almost linear with the dynamic load. However, for a thin pavement (80 mm bituminous thickness), the dynamic load had much less effect on the strain at the bottom of the bituminous layer. They suggested that this behaviour was a function of the changing tyre imprint, where a greater dynamic load (at constant tyre pressure) would result in increased contact area. Deeper from the surface (i.e. at the botttom of a thicker asphalt layer) changes of the contact area can be expected to have a lesser effect than the load change itself. Close to the surface (i.e. at the botttom of a thin asphalt layer) the influence of changing load size is lessened by the increased area over which the load is distributed. This results from the application of St Venant's principle (see 4.3.5.1). If such a result is confirmed by other experiments, then it is clear that the local road network will also need to be carefully considered in the COST 334 work.

4.3.3.8 Summary

The work of COST 334 is particularly applicable to flexible pavement constructions as used on motorways and principal roads in most European countries. However, the thinner flexible roads used in many local authorities must also be included because of the substantial amount of heavy goods traffic they carry, and because of the possibility that their response to dynamically applied loads may be different from that of the thicker constructions.

On the basis of work carried out by COST 333, and by COST 336, it was proposed that flexible pavement constructions in the range 75 - 350 mm thickness of asphalt, with appropriate foundations, should be examined by the COST 334 group. Such pavements should reflect typical design cases for traffic in the range 5, 10 and 100 msa, and should comprise materials having elastic characteristics typical of those used in Europe.

Combining the information of the previous sections, four sample constructions were chosen as representative structures for numerical simulations of pavement response and performance in later stages of the work of Task Group 3. These are shown in Table 4.6. A traffic speed between 50 and 80 km/h was also chosen for these calculations.

Table 4.6 – Representative pavement structures for numerical simulations

	no 1	no 2	no 3	no 4
Traffic intensity	low volume	medium volume	high volume	high volume
Asphalt thickness (mm)	100	200	330	280
Asphalt Young's modulus (MPa)	7,500	7,500	7,500	7,500
Asphalt Poisson's ratio	0.4	0.4	0.4	0.4
Granular layer thickness (mm)	300	250	200	-
Granular layer Young's Modulus (MPa)	200	200	200	
Granular layer Poisson's ratio	0.3	0.3	0.3	
Cement bound base layer thickness (mm)	-	-	-	200
Cement bound base Young's modulus (MPa)				10,000
Cement bound base Poisson's ratio				0.2
Subbase Young's modulus (MPa)	70	70	70	70
Subbase Poisson's ratio	0.3	0.3	0.3	0.3

4.3.4 Global description of tyre - pavement interaction

4.3.4.1 Introduction

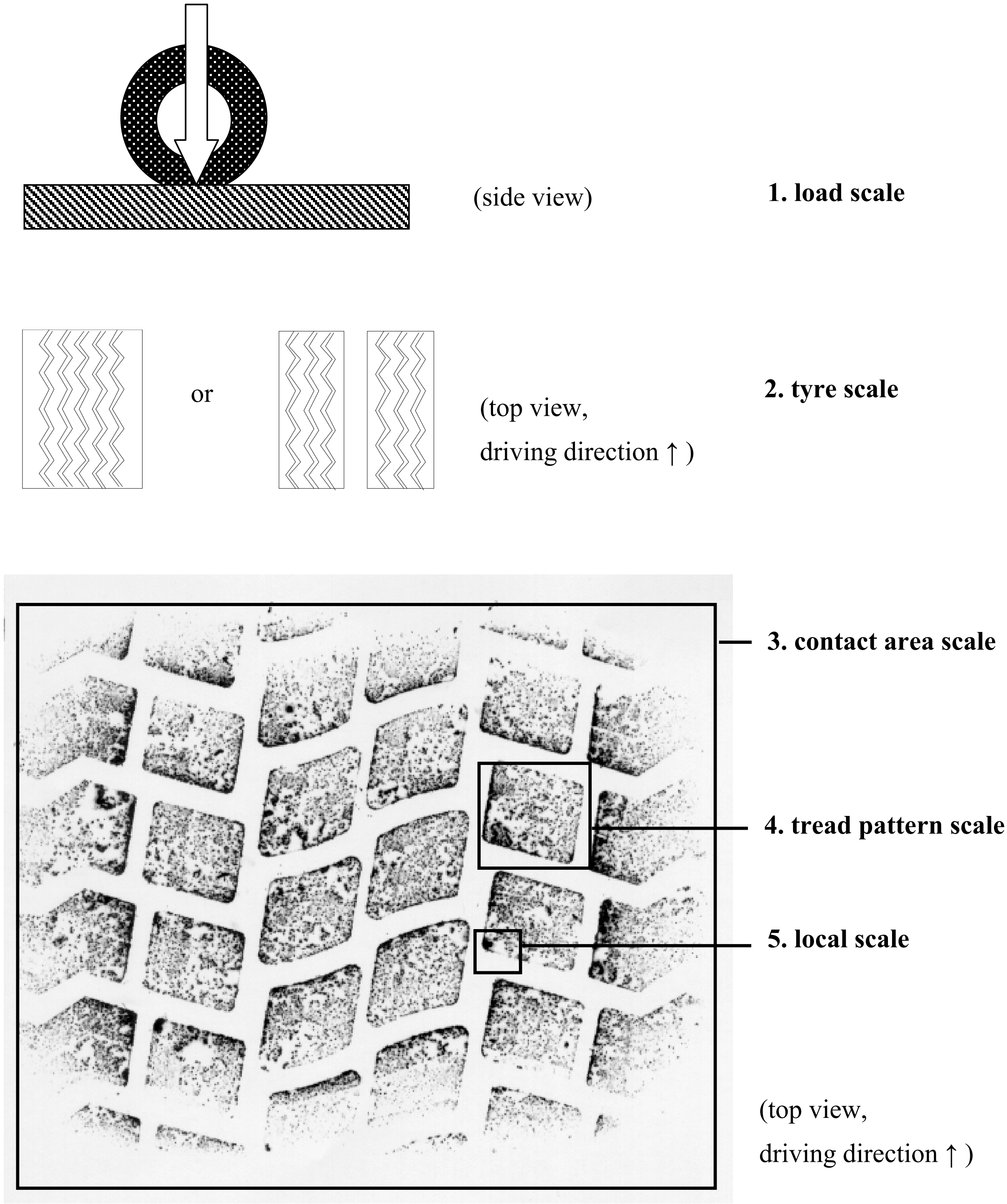
For a proper evaluation of the interaction between tyres and pavements which may lead to pavement wear, some understanding is required about the forces and stresses that act at the tyre- pavement interface, and about the resulting stresses and strains at various depths in the pavement structure.

The vertical force is the wheel load (composed of static and dynamic components). Often, only the vertical forces are considered, but also horizontal forces can occur, due to acceleration, deceleration, steering, ascent or descent of the vehicle and/or inclination of the pavement. Besides, extra interface stresses may occur due to the deformation of tyre and pavement. These latter stresses don’t generate net resultant forces at the interface.

Five different ‘scales’ were considered for tyre-pavement interaction. These are different levels of schematisation, each with their appropriate degree of detail and accuracy. This is like looking through different magnifying glasses with different magnifications. Clearly, the higher levels of schematisation will have a lower degree of accuracy, but this may be sufficient for pavement design purposes.

- The first one can be called the ‘load scale’. At this scale only the value of the net forces is considered, not the area over which it is spread, or the stress distribution within that area.
- The second scale can be called the ‘tyre scale’. At this scale, a distinction is made whether the load is applied by a single tyre (resulting in one contact area) or by a dual tyre assembly (resulting in two separated contact areas).
- The third one can be called the ‘contact area scale’. At this scale, the tyre-pavement stresses are considered to be constant across the tyre-pavement contact area (decimetric scale). The considered stresses may be computed as the ratio of the different exerted forces by the contact area value.
- The fourth one can be called the ‘tread pattern scale’. At this scale, the tyre-pavement stresses are considered to be constant across the tread pattern parts or ribs. The order of magnitude of the concerned surface is of several hundreds of mm^2 (centimetric scale).
- The fifth one can be called the ‘local scale’. At this scale, millimetric gradients are considered.

These scales are illustrated in Figure 4.8 and will be discussed more in detail in the following sections.



(Different intensities of gray in the footprint picture indicate different magnitudes of vertical contact stress, measured on an actual pavement surface.)

Figure 4.8 – Illustration of the five different 'scales' of tyre-pavement interaction

4.3.4.2 The load scale

At this scale only the magnitude of the load is considered. This load magnitude is particularly important for e.g. bridge design, but also for pavement wear. At this scale, not only the static loads have to be considered but also the dynamic loads. The static loads are determined by the vehicle weight and its distribution over the vehicles's wheel assemblies.

The vertical dynamic loads are determined by the vertical vehicle motions and its suspension system. Horizontal dynamic loads are determined by the forces needed for e.g. acceleration, braking, steering or ascent of the vehicle.

Due to the definition of the load scale, at equal loads there is no difference between different tyres at this scale (although different tyres may cause different dynamic loads at the same level of static load). Therefore it falls mainly outside of the scope of COST 334, as stated in section 4.2.

At a distance from the load, the main influencing factor for the stresses and strains in the pavement is the magnitude of the wheel load, independently from the way it is applied (this follows from the application of St. Venant's principle, see 4.3.5.1). This is particularly the case for the lower pavement layers and for the subgrade of the pavement. (Huhtala et al 1989, Halliday et al 1997, among others). So, at this distance, the stresses exhibit no noticeable difference between the tyre types (at equal wheel load) and, thus, will not be further discussed within this chapter. However, this distance (where only the load magnitude counts, and not its distribution) may well be larger than the pavement thickness, especially for thin pavements (Huhtala et al. 2000a). In those cases, the stresses and strains which are relevant for asphalt fatigue or rutting in granular layers (see 4.3.5) are influenced by the tyre-pavement contact area and the stress distribution thereupon, which are discussed in the following sections.

4.3.4.3 The tyre scale

At this scale, distinction is made between the number of areas (tyre footprints) over which a load is distributed. This distinguishes between one contiguous area for wide base and ordinary single tyres, and two areas, separated by some distance, for dual tyre assemblies. The size of these contact areas, or the stress distribution within these areas is not considered at this scale.

The significance of this scale lies in its influence on the stresses and strains in the pavement. The distance between the tyres of a dual assembly (and the absence of such distance for a wide base single) widens the area over which the load is distributed, reducing stresses and strains at many points in the pavement structure.

4.3.4.4 The contact area scale

At this level of schematisation, the average vertical stress considered is the ratio of the applied load to the contact area value. It depends mainly on the tyre inflation pressure, the applied load and on the tyre design.

When a uniform, free rolling, wheel motion is applied on a flat pavement, the longitudinal stress corresponds to the tyre rolling resistance and is very low. It is lower for wide base single tyre assemblies, which have a lower rolling resistance level.

For vehicle acceleration, turning, climbing, braking, or even a uniform vehicle motion (overcoming air resistance as well as rolling resistance) horizontal forces have to be transferred by some of the vehicle’s tyres, giving rise to larger horizontal stresses. When such a driving or braking torque is applied on the tyre assemblies, its effect has to be taken into account.

When no transversal force is applied, the transversal exerted stress is equal to zero. If a transversal force is applied on the tyre assemblies (e.g. when the vehicle is turning), its influence has to be taken into account.

This scale is very important when road wear is considered. Indeed, it is relevant for the intermediate and upper pavement layers in which fatigue and rutting may occur. For the stresses and strains in the pavement (as opposed to the interface stresses), not only the size of the contact area is important, but also its shape. There will be differences in stresses in the pavement between e.g. a wide and short contact area, a square area, a circular area, or a narrow and long area (all having equal area size and vertical contact stress).

4.3.4.5 The tread pattern scale

interface stresses

At this scale, the tyre-pavement interface stresses are considered to be constant across the tread pattern parts or ribs. Many studies have been conducted at this scale. See, for instance De Beer et al (1996), Neddenriep et al (1996), Groenendijk et al (1997) and Blab (1999). (These researchers all considered stresses at the local scale too, as e.g. the transverse contact stress varies considerably over the tread rib width.)

A general description for a free rolling wheel is given below. In addition, extensive data and explanations can be found in Clark (1982). Furthermore, Figure 4.9 shows some results of De Beer et al (1996) for a free rolling (no torque applied, nor lateral force) Bridgestone 425/65R22.5 radial wide single tyre. Wheel load was 50 kN (the rated maximum for this tyre) and inflation pressure was 900 kPa. As the recommended pressure was 830 kPa cold for the rated wheel load, the actual pressure is close to the recommended pressure in warm conditions. Wheel speed was about 16 km/h.

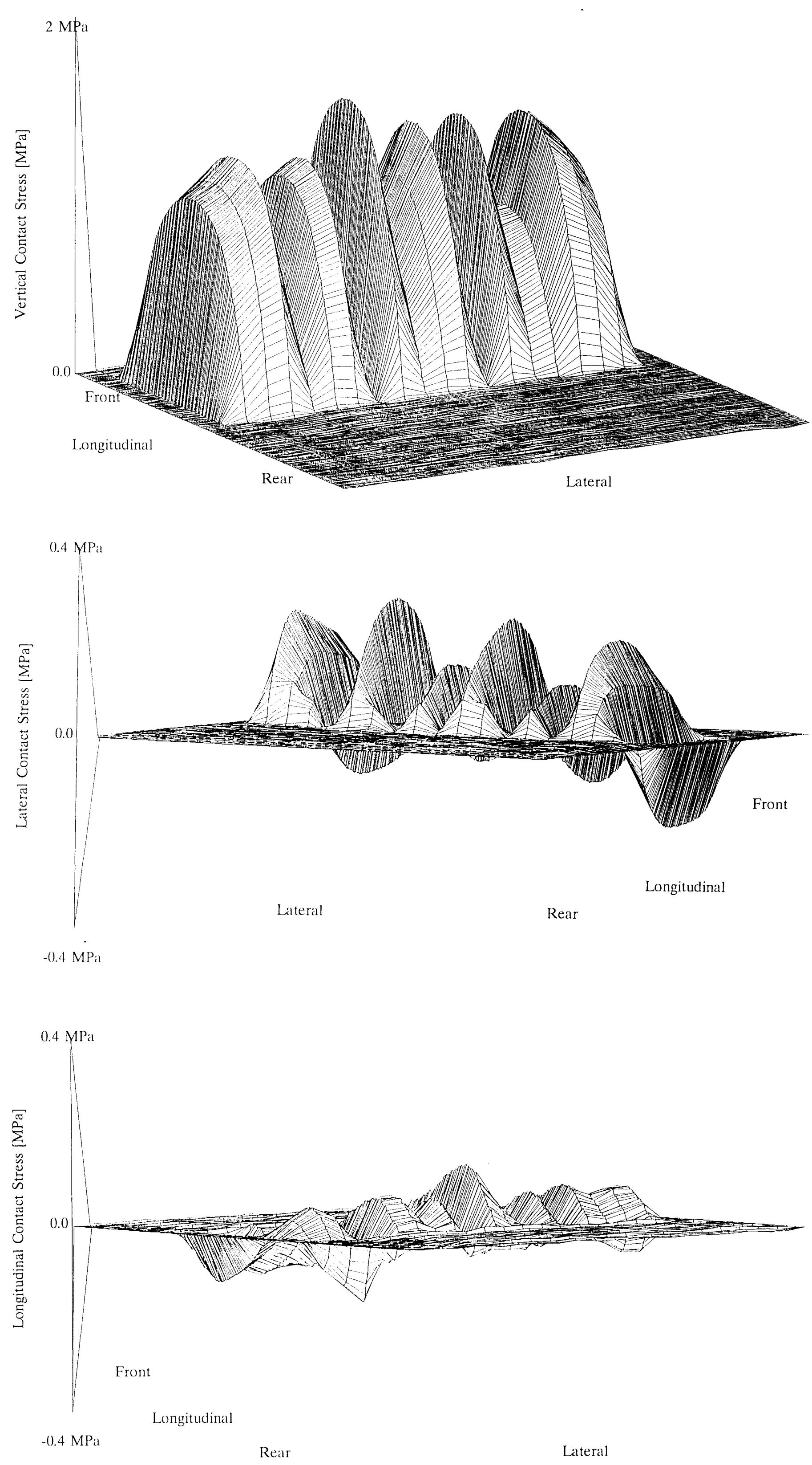


Figure 4.9 – Examples of vertical (top picture), transversal (middle) and longitudinal (bottom) tyre-pavement interface stresses (De Beer et al 1996)

Figure 4.10 shows a simplified representation along a tread rib (X direction) of the stress in the three directions. X is the longitudinal direction, Y the transverse and Z the vertical one.

There are two symmetrical transverse (Y-)stress curves, corresponding to symmetrical ribs in respect to the tyre symmetry plane (the sum value for the entire tyre is equal to zero).

These curve shapes derive directly from the fact that a curved surface (tyre) is pressed to a flat surface (pavement) when the load is applied and from the fact that rubber has a Poisson ratio very close to 0.5. (If the surfaces are larger it would be likely that the shear stresses are greater.) The proportions and shapes of the curves are modulated across the tread width. They are also modified by external longitudinal and transversal actions.

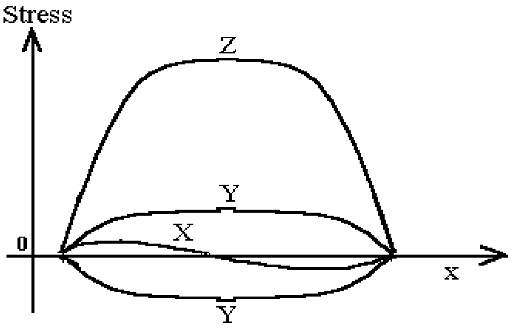


Figure 4.10 - Tyre – pavement contact stresses at the tread pattern scale

At this scale, the tyre/pavement contact area can be divided in three zones in transverse direction: two edge zones of about 20% of the tyre width each, and one centre zone covering the remaining approximate 60%. The stress distributions vary between these zones.

The vertical contact stresses can be simplified as uniformly distributed over each of the zones, but generally with different values for the centre and edge zones. The stress level in the centre zone is mainly determined by the tyre pressure and hardly influenced by the wheel load. The edge zone level is mainly determined by tyre design, wheel load and tyre pressure.

The longitudinal distribution of the longitudinal stresses is roughly sine-shaped, with predominantly backward stresses in the front half of the tyre and forward stresses in the rear half. Often, however, this roughly sine-shaped distribution has an offset, resulting in unequal maxima and minima. This occurs especially at the tyre edges (in overloaded condition). It seems that both the amplitude and the offset of the distribution vary between the edge and centre zones.

The transverse stresses can be modelled roughly as constant over the tyre length. The transverse distribution of the transverse stresses is a matter of the local scale and therefore will be discussed in the next section.

The vertical stresses in Figure 4.9 are distributed rather uniformly over the tyre width (except for the sipes). This corresponds to a proper match of wheel load and tyre pressure, as recommended by the manufactures. Figure 4.11 shows the influence of ‘underloading’ (i.e. smaller load than recommended for the actual inflation pressure, this is similar to overinflation) and overloading. The inflation pressure is 900 kPa, like in Figure 4.9, but the wheel load is 25 and 75 kN respectively. The stresses under the centre 60% of the tyre width remain rather constant, but the stresses near the tyre sidewalls are influenced rather strongly. Overloading may lead to stresses near the tyre sidewalls which can be considerably larger than the inflation pressure.

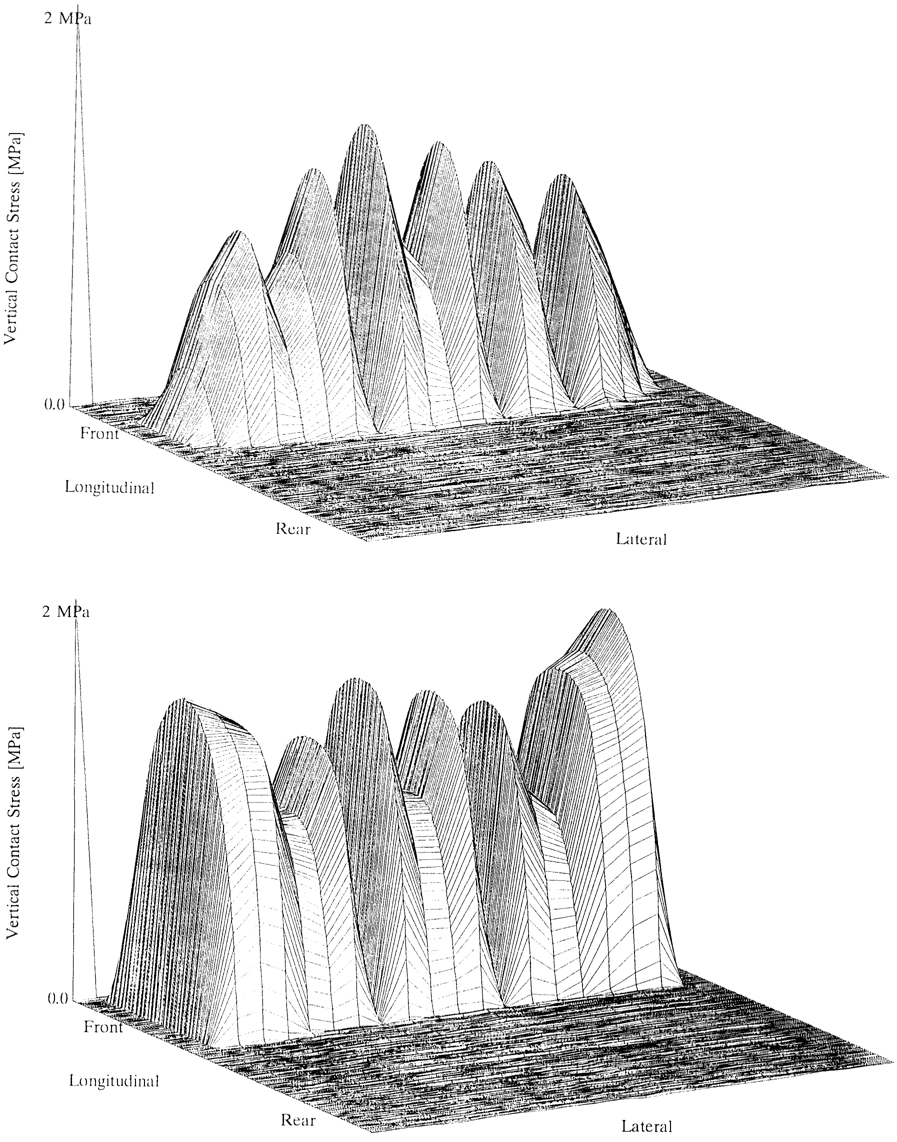


Figure 4.11 – Examples of vertical tyre-pavement interface stresses at 'underloading' (i.e. relative overinflation) (top) and overloading (bottom) (De Beer et al 1996)

<u>stresses in the pavement structure</u>

The interface stresses exerted at the tread pattern scale may have an influence on the surface pavement layers, especially in respect to rutting in the bituminous layers, and probably also in respect to ravelling and surface cracking. However, commercial vehicles are not channelized on the roadways and their lateral trajectory dispersion is higher than the tyre assembly contact area width and much higher than the tread pattern width. Thus, the potential influence of stress modulation (peak stresses) on the tread pattern scale may be diminished by the influence of the effective multiple tyre positions on the road way lanes.

It is also diminished by the fact that the tyres are of different sizes and different tyre brands with different tread pattern geometries (see Huhtala et al 1989, 1997, amongst others). These different geometries induce a very important variability of stress distribution at the tread pattern scale and no general tendency can be drawn.

Moreover, for the same brand and tyre size, different tyre types and different wear rates will exhibit different stress distributions at this same scale. See de Beer et al (1996) with data on two Bridgestone 425/65R22.5 tyres.

Lacking data about the detailed distribution of contact stresses for all relevant tyres, at present, it would be illusive to consider the stresses exerted at this tread pattern scale for road wear concern. Indeed, on roadways, the observed ruts are very smooth and do not exhibit different depths on a centimetric scale in the transversal direction.

4.3.4.6 The local scale

This is the millimetric scale of the tyre local tread pattern details, such as sipes (tread grooves) andalso the scale of the pavement texture (sand and stone partice size). As shown in the previous section, this is also the scale of the variation of the transverse contact stresses over the width of the tread ribs.

The transverse distribution of the transverse stresses can be modelled by a combination of two effects, shown in Figure 4.12.

Firstly, there is a zigzag distribution of outward shear underneath each tread rib (‘outward’ relative to the tread rib centre), caused by the fact that the rubber of the tread rib is loaded vertically and therefore wants to expand horizontally. This expansion is impeded by the friction between the tyre rubber and the laterally much stiffer pavement. The amplitude of this zigzag is determined by the vertical contact stresses, width (and probably height) of the tread rib, the friction coefficient and the stiffness moduli of the rubber and the pavement.

Secondly, a zigzag distribution over the full tyre width may exist, in case of relative overinflation / underloading (giving outward shear), or underinflation/overloading (giving inward shear).

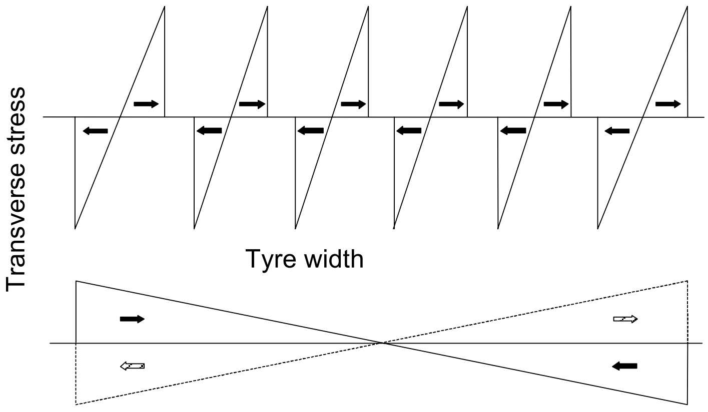


Figure 4.12 – Transverse distribution of transverse contact stresses underneath treaded tyre. Top: due to compression of tread ribs. Bottom: due to overloading / underinflation (solid line) or ‘underloading’ / overinflation (dotted line)

The knowledge of tyre-pavement stresses at this scale is very important for tyre adherence and, thus for safety. Indeed, on the edges of the tyre sipes or tread pattern parts, the local pressure must be high to ensure that the water film is broken on wet roads.

This scale can be seen in Figure 4.8, where the white patches in the tyre footprint are due to local non-contact because of pavement texture, and the black ridges along the tread pattern edges indicate the high stresses there.

The induced stress modulation may be important for surface distress as raveling or surface cracking.

However, this scale is much smaller than the lateral wander. The induced stress modulation is too local when related to deeper road wear, like deformation of bituminous layers. Its influence on this deformation is also diminished by the fact that the tyres are of different sizes and different tyre brands with different tread pattern local geometries. Indeed, on roadways, the observed ruts do not exhibit tread pattern pictures.

4.3.5 Pavement distress modes

4.3.5.1 Introduction

It is well known that pavement wear is a process in which several different deterioration processes act and interact, influenced by a variety of factors. (These factors include environmental factors such as temperature and moisture, but only the traffic-related factors will be considered here.) Therefore it is attempted to separate the influences of tyre type (single / dual / wide single), tyre size, wheel load, inflation pressure[1], pavement material (by concentrating on flexible pavements) and asphalt thickness. Furthermore, a distinction has to be made into different modes of distress. This is elaborated in section 4.3.5.2.

It is to be expected that these different distress modes react differently to changes in the influencing factors, such as tyre type. This is explained by the application of St Venant's principle to our case: "The stress and strain conditions near the surface of the pavement are strongly influenced by the contact stresses and their distribution in the tyre-pavement interface, whereas the stresses and strains deeper in the structure are mainly influenced by the total load." Therefore, a change in contact stress distribution due to a change in tyre type can generally have most influence on the upper layers[2].

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[1] Tyre type, tyre size, inflation pressure and other tyre related factors are generally held to influence the pavement distress through their influence on the contact area and contact stress distribution in the tyre-pavement interface. ("The pavement material does not care by what tyre it is loaded, but only by what stresses.") These influences on the contact stress distribution are highly non-linear.

[2] However, exceptions to this rule may occur, depending on structure and material quality (e.g. a very critical stress-sensitive granular layer below a rather thick AC layer may be the main cause of rutting increase due to a slight increase in stresses).

4.3.5.2 Pavement distress modes

Pavement wear or pavement distress is the reduction of pavement quality due to loading by traffic and/or climate. For flexible pavements, the following distress modes (visible distress together with the deterioration process causing it) are relevant:

- cracking
    - fatigue cracking, being cracking in the bituminous or cement bound material originating at the bottom of the respective layers, due to fatigue of the material by a great number of repetitions of bending due to wheel loads (Fatigue defined in this way is used as a parameter in pavement design. This does not include surface cracking and cracking due to thermal cycling, although these are also due to fatigue because of repeated stress cycles.)
    - thermal cracking, being cracking in the bituminous material due to tensile stresses caused by temperature changes
    - surface cracking, being cracking in the bituminous material originating at the surface of the pavement, due to fatigue of the material by a great number of shear loadings of the pavement surface by the tyre (Ageing of bituminous materials plays an important role here, too.)
    - reflective cracking, being cracking of the (top) bituminous layers (often in a composite structure) as a result of cracks or joints in bound layers below. (This is not studied here.)
- rutting, being the development of depressions in the pavement surface along the wheel paths, typically with a width of several decimetres and a length of tens to thousands of meters
    - rutting due to permanent deformation of bituminous layers, in this report also called ‘primary rutting’ (Permanent deformation can be due to (post)compaction or (plastic and viscous) deformation caused by shearing stresses.)
    - rutting due to permanent deformation in the subgrade or in granular layers below the asphalt layers, in this report also called ‘secondary rutting’
    - rutting due to abrasion of the pavement surface by studded tyres. (This is not studied here.)
- ravelling, being the loss of stones in the surface of the pavement as a result of failure of the bond between the aggregate and the binder by a great number of shear loadings in combination with ageing of the material.
- roughness, being (longitudinal) unevenness of the pavement, mostly due to several combined factors (rutting, cracking, potholes, uneven settlements, etc.)
- potholes, resulting either from local collapse due to structural defects, or from frost acting on water ingress (often through cracks)

The more important of these distress modes are shown in Figure 4.13.

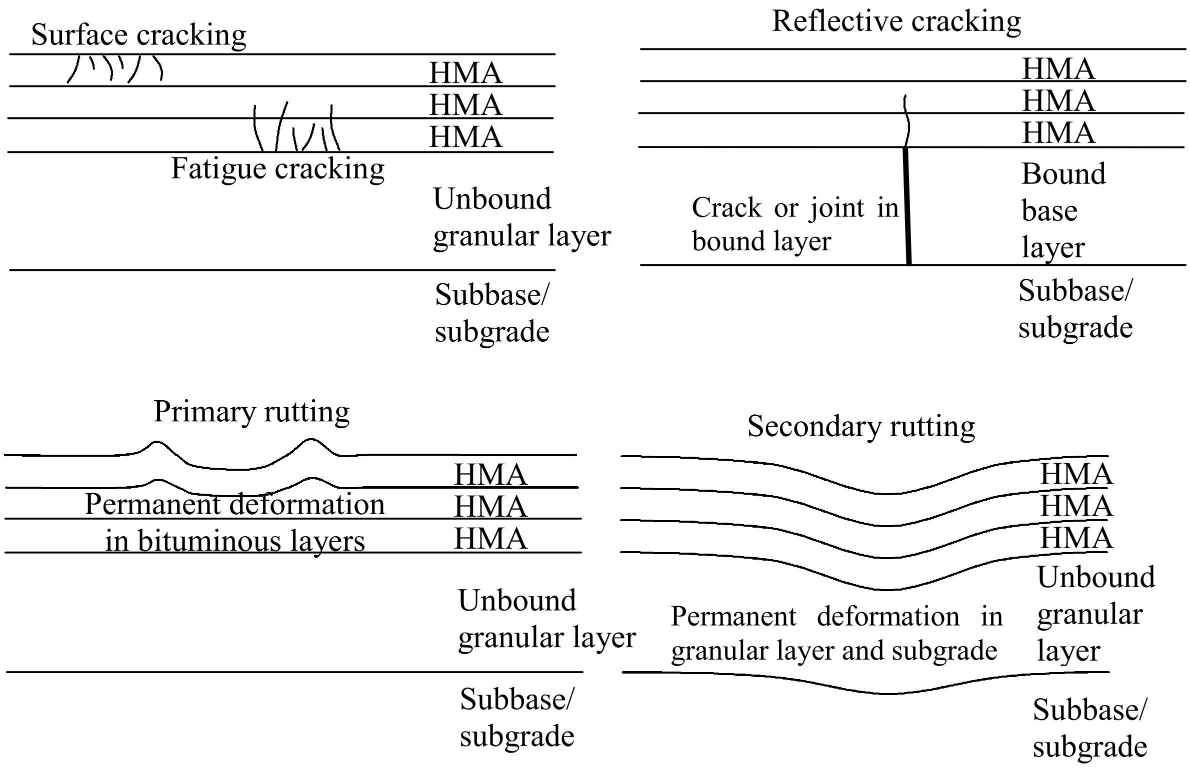

Figure 4.13 – Various modes of pavement distress

The main distress modes, especially from the point-of-view of traffic loading are:

- Fatigue cracking. This occurs mainly on relatively weak / thin pavements (Visible cracking in thick pavements is likely to originate (at least partly) at the surface.)
- Primary rutting. This occurs mostly on main roads with thick bituminous layers.
- Secondary rutting. This occurs mainly on relatively weak / thin pavements.

Most design methods for flexible pavements since the 1960s are based on the prevention of fatigue cracking and secondary rutting. In relatively weak /thin pavements this does not always succeed, but in thick pavements it generally succeeds. Then, primary rutting may become the dominant distress.

Permanent deformation of bituminous layers is usually not considered as a part of structural design. With proper bituminous mixture design the tendency for permanent deformation can be decreased. However, the bituminous mixture design is always a compromise between many properties (including price) and small changes in mixture composition during the manufacturing may worsen the properties of bituminous mixtures. It is possible to manufacture mixtures, which will not deform easily, by using modified bitumens but they are much more expensive and thus their use is limited.

Ravelling and surface cracking, being the most superficial distress modes, may be influenced by any differences in contact stress distributions between different tyre types. These distress types were not studied in detail by TG3, however, both because they are of lesser practical importance, and because their mechanisms are not fully understood and therefore the quantification of differences between tyre types would be extremely difficult.

4.3.6 Load effects

4.3.6.1 Introduction

This section describes the influence of several load effects. First, the effect of different load sizes is described in section 4.3.6.2, explaining the concept of Load Equivalency Factors. It is important to realise that the actual forces on the road are not equal to the static axle loads, but vary because of vehicle dynamics. This is elucidated in section 4.3.6.3. Also, the effect of axle loads may be influenced by neighbouring axles, as explained in section 4.3.6.4. Another factor to be taken into account is the lateral wander of the traffic, elaborated in section 4.3.6.5. Finally, section 4.3.6.6 discusses the load sharing between twinned tyres.

4.3.6.2 Relative effects of different axle loads

For pavement design, but also to determine the pavement wear effect of different tyres, the pavement wear effects of different axle loads have to be determined. Generally this is described by a Load Equivalency Factor (LEF), where an axle load is said to be equivalent (producing equal pavement wear) to a number of applications of a reference (standard) axle load. The most well-known of such a LEF is the so called "fourth power law" which is expressed mathematically as follows:

$$\frac{N_y}{N_x} = \left(\frac{P_x}{P_y} \right)^4$$

where P_x and P_y are axle loads and N_x and N_y are the corresponding number of load applications.

The exponent 4 in the fourth power law was found in the AASHO Road Test. However, it was not strictly constant in that test but varied from about 3.6 to 4.6. Later experimental and theoretical research has indicated greater variability in the exponent, but has not been conclusive. As an example, it was found in the OECD FORCE project that the exponent depends also on the extent of distress, the exponent being smaller in earlier phases than in later phases of failure.

It must be understood that the fourth power law includes all distress modes. The most important at the AASHO road test were rutting (caused by subgrade deformation) and roughness (unevenness) of the road. Cracking had a minor effect and deformation of bituminous mixtures was not important.

When individual distress modes are considered, different exponent values are found, corresponding with the exponents in the performance relations mentioned in section 4.3.7. Cracking of bituminous layers has a value of 4 to 7, permanent deformation of the subgrade has an exponent of perhaps 3 to 4 and permanent deformation of bituminous layers a value of 1 to 2. Unfortunately, these values depend on many factors (a.o. material variations) and are not fully known. Therefore, the stated values represent "best estimates".

For use in pavement design, where the actual spectrum of axle loads has to be converted to an equivalent total number of standard axle loads, it was found that the precise exponent value is not very important. For exponent values between 2 and 6, most actual axle load spectra were found to translate to roughly the same equivalent number of standard axles. (For low exponents, the multitude of smaller axle loads contribute the bulk to the total equivalent number. For high exponents, the few overloaded axles contribute the most.) Therefore, the "overall" value of 4 is well suited.

For detailed studies into pavement wear effects, such as attempted here, the exponent values for the individual distress modes should be distinguished. This is especially the case when conclusions should be drawn from accelerated tests at high load values.

4.3.6.3 Dynamic axle loading

When a vehicle is not moving, the vertical (axle, wheel and tyre) loads it imparts on the pavement, due to the force of gravity, are constant. These are the static loads. When the vehicle is moving along a road, however, unevenness of the road will cause the vehicle to move up and down. This will cause a dynamic variation of the loads on the pavement, above and below their static values.

The magnitude of this dynamic variation depends on the vertical dynamics of the vehicle, including such factors as the mass and stiffness distribution of the vehicle structure, payload mass distribution, suspension and tyres, and on the road surface's longitudinal profile and the speed of the vehicle. The variation generally increases with both speed and road unevenness.

The magnitude of dynamic loads is mostly expressed as the Dynamic Load Coefficient (DLC), defined by the OECD as the ratio of the RMS (root mean square) dynamic wheel load to the mean wheel load. The RMS of the dynamic wheel load is essentially the standard deviation of the probability distribution of the total wheel load. The mean value reflects the static wheel load. So, the DLC is the coefficient of variation of the total wheel load. This is reported to range between 5 to10% for well-damped air suspensions and soft, well-damped steel leaf suspensions, and between 20 to 40% for less road-friendly suspensions (OECD 1992).

Dynamic loading increases pavement wear. Because of the power-law dependency of pavement distress on axle loads (see section 4.3.6.2), the loads above the static load increase the pavement wear more than the decrease in wear due to the loads below the static load.

Besides load magnitude, also frequency content is important for pavement wear. Most heavy vehicles have dynamic wheel loads either in the 1.5 to 4 Hz range, associated with bounce (up/down) and pitch (rotating forward/backward) motions of the vehicle body, or in the 8 to 15 Hz range, associated with axle-hop vibration. Axle hop vibrations are more significant if the pavement is rough and the vehicle speed is higher than approximately 40 km/h.

As stated before, the tyre characteristics (vertical spring compliance and damping) influence the dynamic vehicle loads. Therefore, these should be considered when establishing pavement wear effects of different tyres.

4.3.6.4 Relative effects of single axles, tandem axles and tri-axles

Tandem axles and tri-axles (see the definitions in section 4.10) generally cannot be treated by summation of the effects of their constituting individual axles, because of two reasons.

- The load spreading of thick pavements may be such that the responses (stresses and strains) due to neighbouring axles in a tandem or tri-axle configuration may substantially increase the responses under the axle considered. Due to the non-linearity of the performance relations, such increased responses will lead to much more pavement wear than the summed responses of individual axles.
- Due to the visco-elastic nature of bituminous materials, stresses and strains caused by an axle load need some time to relax after the axle has passed. When another axle

arrives within that period, some residual stresses and strain will still be present, which may compound with the stresses and strains caused by the new axle, resulting in higher total values. The effects of this mechanism are not well understood.

For axle load limitations, this is reflected in maximum allowed tandem axle (and tri-axle) loads which are less than twice (or three times) the allowed single axle load. (Two axles at more than 1.8 m spacing are not considered a 'tandem axle' but a 'double axle' and are treated as two single axles.)

For pavement design purposes, however, the loads of tandem axles and tri-axles are mostly converted to a number of 'equivalent standard axle loads' (N_{esal}) by summing the contributions of the individual axles. These individual contributions are mostly calculated using the Load Equivalency Factor described in 4.3.6.2., resulting in:

$$N_{esal} = \sum_{1}^{\text{nr of axles}} \left(\frac{P_{\text{axle}}}{P_{\text{standard axle}}} \right)^{4}$$

TG3 decided to provide for separate mention of the effects of tandem axles and tri-axles, but to exclude this aspect from their work, as it was considered to be not relevant for the difference between dual and single tyres. In practice, the chosen tyre type is related to the axle configuration, but these relations were not investigated by TG3.

4.3.6.5 Lateral wander

In practice, not all wheels will pass at the same lateral position in a road section. Vehicles generally follow a slightly zigzagging course between the bounds of the traffic lane, which is called lateral wander. Therefore, the wheel positions of consecutive vehicles will be transversely distributed over the pavement.

Detailed measurements and analysis of this distribution are reported by Blab (1995). He showed that the probability distribution of the vehicle positions is a Laplace distribution, in stead of the normal distribution that is often assumed. For a certain vehicle width and lateral wheel spacing, the probability distribution of the wheel (centre) positions is a Laplace distribution, too. However, the number of 'hits' by a tyre per cm pavement width is approximately normally distributed, due to the summation over various vehicle widths, wheel spacings, dual and single wheels, and various tyre widths. The difference is shown in Figure 4.14.

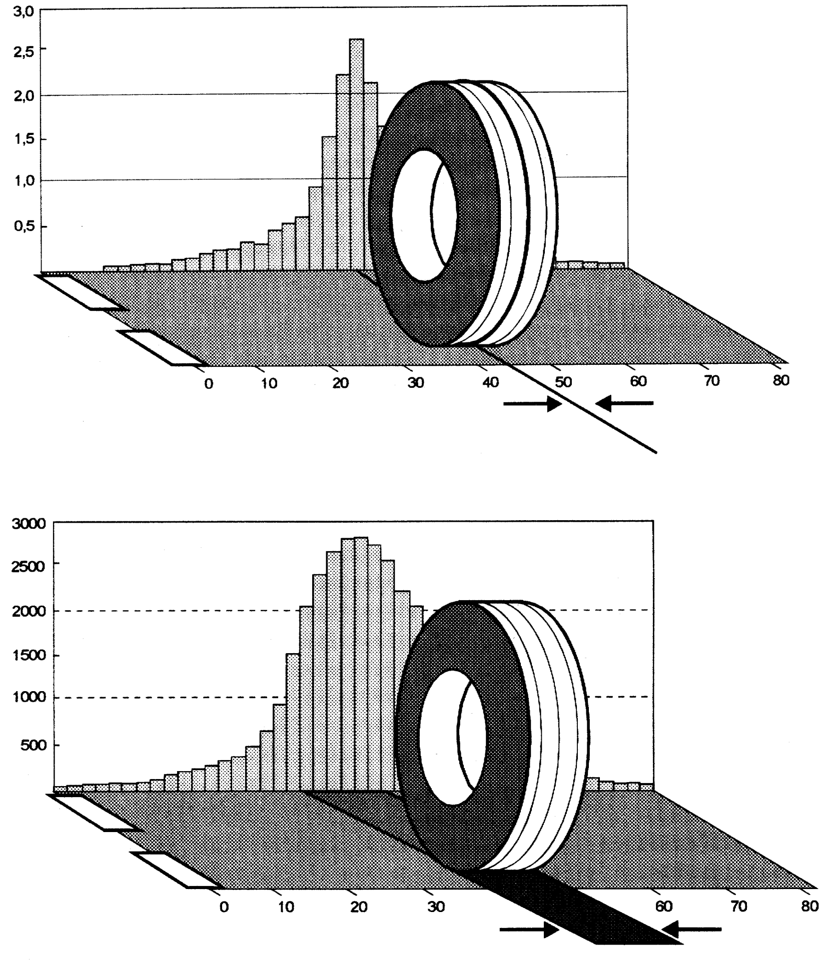

Figure 4.14 – Difference between probability distribution of the wheel positions (a) and the number of hits by a tyre per cm pavement width (b) (Blab 1995)

Lateral wander distributes pavement loading, and hence pavement wear, over a larger area of the pavement. This prolongs the pavement service life. The effects of lateral wander are different for the different distress modes. They also may differ between dual tyres and wide base singles.

4.3.6.6 Unequal load sharing of twinned tyres

When comparing dual and single tyre assemblies at equal wheel load, generally the assumption is made that the wheel load is shared equally between both tyres of the dual assembly. However, in practice this might not be true. A number of reasons could cause an unequal load division ('load imbalance') between both tyres:

- differences in vertical stiffness between both tyres, because of
  - differences in inflation pressure (mainly due to poor maintenance)
  - different tyre structure (due to e.g. different brands)
- differences in vertical compression between both tyres, because of
  - differences in diameter between both tyres
  - bending of the vehicle axle
  - transverse unevenness of the pavement surface

These reasons are illustrated in Figure 4.15.

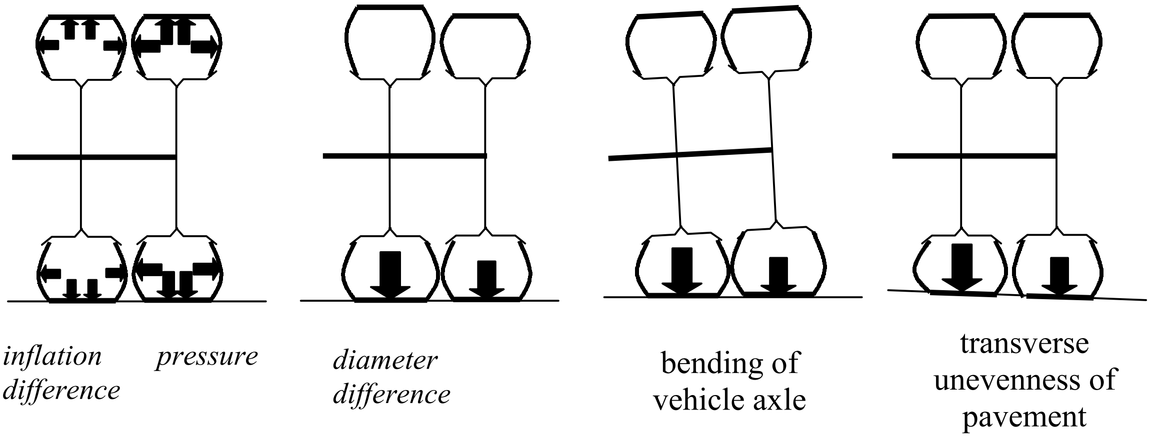

Figure 4.15 – Causes for unequal load sharing between tyres in a dual tyre assembly (‘load imbalance’)

Due to the non-linear relationship between load and pavement distress, the tyre with the larger load will cause disproportional more pavement wear. Therefore an ‘imbalanced’ dual tyre assembly will cause more pavement wear than a properly ‘balanced’ dual assembly. This factor may influence the comparison of dual and single tyre assemblies.

4.3.7 Methods for assessing pavement performance

4.3.7.1 Classification

Three methods are distinguished to estimate the (relative) damaging effects of wheel load configurations, based on the two-stage analysis approach (response / performance), commonly used in so-called ‘mechanistic’ (or ‘mechanistic-empirical’) pavement design methods.

The pavement response is the short-term reaction (within seconds) of a pavement to an external load, generally specified as the mechanical stresses and strains in the pavement due to the load. The performance is the long-term reaction (over years, generally) of a pavement to the summation of a large number of loads, generally described by the development of pavement distress. In mechanistic design the performance is predicted from the response, relating critical strains and stresses to particular distress modes using empirical/laboratory performance relations. (E.g. the maximum tensile strain at the bottom of a bound layer is generally related to fatigue cracking. Similarly the maximum vertical strain or stress at the top of the subgrade is generally related to permanent deformation of the subgrade). These relations often have an power-law shape: $N = \varepsilon^{-n}$, where ε is the strain response due to a load, N is the allowable number of repetitions of that load, and the coefficient n is dependent on material type and distress mode.

The three types of study to estimate the (relative) damaging effects of wheel load configurations are:

1. Full mechanistic modelling (modelled response, modelled performance)

These are purely modelling studies employing both stages of the mechanistic analysis procedure. Response models are employed to predict the critical strains for the different wheel load configurations, and the mechanistic-empirical performance relations are used to translate these to relative damage ratios.

2. Response measurements (measured response, modelled performance)

These studies are based on measuring the actual response of representative pavements under different wheel load configurations. The more recent studies measure critical strains (or strain ratios) and the mechanistic-empirical performance relations are used to translate these to relative damage ratios. So, the first (modelling) stage of the mechanistic procedure is replaced by direct measurement.

3. Performance measurements (actually measured performance, possibly accompanied by measured response)

In these studies, test pavements are loaded with different wheel load configurations, and change in pavement condition (pavement performance) is measured directly to determine relative damage rates. As the damage rates are based on direct measurement, this method is independent of the mechanistic analysis procedure.

Both response and performance measurements can be executed using test roads or using accelerated load testing of pavements (ALT), mostly at full scale.

Laboratory tests are necessary to provide the necessary input data for response models and performance relations. For detailed response modelling, also (measurement) data are necessary on the tyre/pavement contact stress distribution.

4.3.7.2 Description, advantages, disadvantages and limitations

(Numerical) modelling in pavement engineering has not yet been able to fully model (to general satisfaction) all relevant aspects of pavement response to external loading and the development of distress over time and repeated load applications. This is due to the complicated behaviour of pavement materials and the large variations thereof[3].For a satisfactory modelling, a three-dimensional (3D) finite element program is required, with a complex modelling of material behaviour. This would be very expensive both in terms of computer capacity and in terms of material testing. The general feeling is that these costs would not be paid back by any savings of a more accurate design, as wide margins of safety have to be used to account for large variations in material properties and loading conditions. Therefore, at present no program is available to determine e.g. all possible effects on pavement wear resulting from changes in tyre characteristics.

Response measurements are measurements of stresses, strains and deflections in the pavement due to wheel loads (e.g. as a vehicle passes the test section). It is possible to study many variables in a short time. The phenomena are real and new ideas can be found during the research (e.g. the importance of unequal load distribution between tyres in dual tyre assembly). Also the effects of changing tyre/pavement stress distribution and contact areas can be seen. Response measurements are good to study the phenomena related to pavement design (horizontal strains at the bottom of bituminous layers, and vertical stresses and strains in unbound layers and the subgrade). A limitation is that no (good?) sensors are available for every purpose, for instance not to study response in bituminous layers related to primary rutting.

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[3] How can other fields of engineering have succeeded, where pavement engineering has not yet? In structural engineering, mostly engineered materials are used, with less variable properties and often more simple behaviour. In soil mechanics, partly the same materials are used as in pavements but generally lacking the temperature dependence of bituminous materials. Furthermore, loading conditions in soil mechanics are often such as to enable 2D modelling, which is much easier than 3D modelling.

Mechanistic-empirical performance relations related to fatigue of bituminous materials and permanent deformation of the subgrade are known well enough, but those for permanent deformation of bituminous layers are not. Furthermore, the latter are highly influenced by (unpredictable) high temperatures.

Long Term Pavement Performance (LTPP) studies and **Test roads** are more or less instrumented pavement sections under normal traffic, of which the performance of the pavements is monitored. LTPP sections are mostly scantly instrumented and are often of regular construction, whereas test roads are mostly extensively instrumented and are often of experimental construction. The advantage of test roads is that the loading is without costs and the loading conditions are true-to-reality, including effects of climate, time, mixed traffic composition and rest periods. Disadvantages are the long test duration (mostly 5…20 years), the variations in loading conditions which complicate data interpretation, difficulties to monitor pavement condition closely while under traffic, and the fact that tests cannot be continued to high distress levels (because of danger to traffic). Special cases of test roads are road tests where the loading is supplied by dedicated vehicles. The most important was the AASHO road test in Illinois in 1958-60. A more recent example is WesTrack in Nevada. The main disadvantage is that such tests are extremely expensive.

Full scale accelerated pavement testing (ALT) means that a pavement is loaded with normal truck wheels by a special testing facility, usually under controlled circumstances. The accelerating effect (relative to normal traffic) can be had with increasing the number of loads per time interval or by applying greater wheel loads than in practice. The effects of load acceleration on pavement performance are generally neglected, but they are not fully understood.

4.3.7.3 Relevancy of the different research methods

Table 4.7 and Table 4.8 show a subjective rating of the relevancy of the different methods.

Table 4.7 – Relevancy of research methods for different distress modes

	Fatigue	Primary rutting	Secondary rutting	Surface cracking	Ravelling
Modelling, response	XX	?	XX	?	
Modelling, performance	XX	X	XX	?	
ALT, response	XX		XX	X	
ALT, performance	XXX	XXX	XXX	XX	X
Test roads, response	XX		XX	?	
Test roads, performance	XXX	XXX	XXX	XXX	XX
Laboratory tests	XX	XX	X		
Tyre/pavement stress distribution measurement		X		XX	

Blank means: “not (yet) applicable”. ? means: “may be applicable but uncertain”. X to XXX mean “applicable”, with increasing experience and validation from X to XXX

Table 4.8– Relevancy of research methods to assess different influencing factors

	Load size	Dynamic load	Uneven load distribution	Lateral wander
Modelling	XX		XX	XX
ALT or test roads, response measurements	XXX	XXX	XXX	XXX
ALT or test roads, performance	XXX	XXX	XXX	XXX

4.3.8 Expressions for relative pavement wear

4.3.8.1 General

When comparing the relative effects of different wheel load configurations, a number of different representations is used by the research community (Senstad et al. 1992). The most common are:

1. the (relative) amount of load cycles to reach the same distress condition (often reported at only one distress condition, generally a 'failure' criterion), e.g. the ratio N2 / N1 or N1 / N2 in Figure 4.16;
2. the (relative) amount of distress at the same number of load cycles (often reported at only one number of load cycles, generally at 'end of test'), e.g. the ratio D2 / D1 in Figure 4.16;
3. the (relative) wheel loads, resulting in equal or equivalent amounts of distress at the same number of load cycles, (again, often reported only at one distress condition and one number of load cycles).

Confusingly, these representations sometimes are used intermingled, with e.g. "four times greater fatigue damage and two times greater rutting", meaning reduction of fatigue life by a factor of four (representation 1. above) and increase of rut depth by a factor of 2 (representation 2 above). Similarly, the term 'load equivalency factor' is sometimes used for representation 1 (as by TG3), and sometimes for representation 3.

Often, however, the relative effects of different load conditions aren't even expressed in terms of performance, but only in terms of (relative) responses.

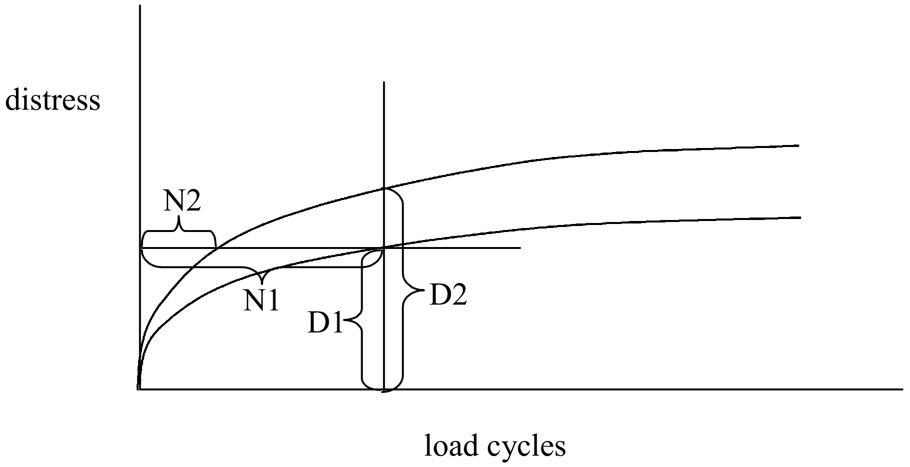

Figure 4.16 - Different expressions for relative pavement wear

Representation 1 is most commonly used. The ‘life ratio’ (or ‘Pavement Wear Ratio regarding Life’, PWR_L) is defined as N1 / N2 as shown in Figure 4.16. This indicates how much faster the pavement deteriorates for condition 2, relative to the reference condition 1. (In other words: how many load cycles of the reference condition 1 cause the same amount of distress as one cycle of condition 2.) This factor is very helpful in attributing pavement costs to different types of vehicle loadings. It relates directly to practice, where load conditions are varied, and the maintenance criterion (amount of distress) is mostly fixed.

It should be noted that the PWR_L value may vary, depending on the amount of distress at which the PWR_L is calculated. This is because it is likely that the distress development curves in Figure 4.16 will not have the same ratio N1 / N2 at all amounts of distress. Therefore, the amount of distress at which a PWR_L is determined should preferably be mentioned explicitly.

Representation 2 is useful for researchers, because it gives an easy way to express the results of a comparative test after a certain amount of unequal loads/conditions. The ‘distress ratio’ (or ‘Pavement Wear Ratio regarding Distress’, PWR_D) is defined as D2 / D1 as shown in Figure 4.16. This indicates how much more the pavement deteriorates for condition 2, relative to the reference condition 1.

Representation 3 can be derived from representations 1 or 2. This representation is helpful when a limit has to be set on the damaging effect of the wheel load (e.g. allowing smaller axle loads on ‘road unfriendly’ suspensions).

Unfortunately, straightforward conversion between these representations is generally not possible, as such conversion is dependent on pavement type/materials/thickness, distress mechanism (and development) and loading conditions. Attempts at such conversions generally involve a mechanistic structural model and assumptions for the mechanistic-empirical performance relations and the distress development as a function of time and progressive load cycles.

However, the values of the PWR_L and PWR_D can be very similar, especially if the distress shows a (near-) linear development with time or load cycles. This is shown in Figure 4.17.

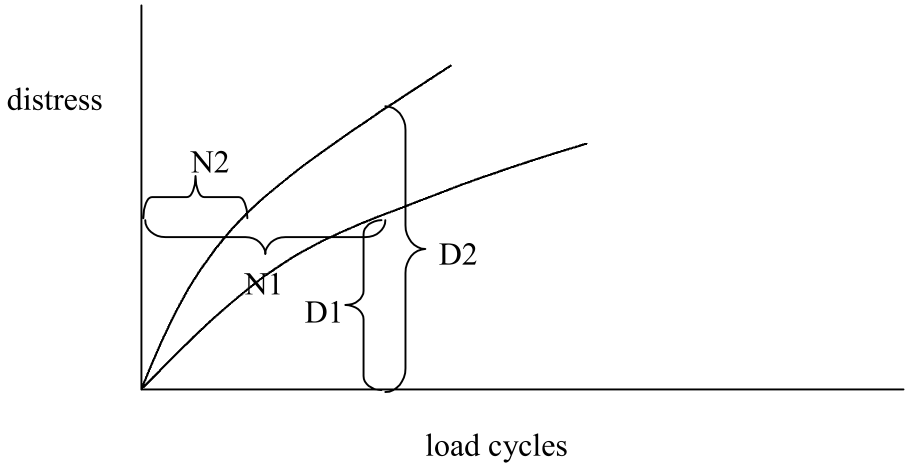

Figure 4.17 – Similarity of Life Ratio and Distress Ratio values for near-linear distress development

4.3.8.2 Representation chosen by Task Group 3

Task Group 3 decided to choose the ‘life ratio’ (PWR_L), described in the previous section, to quantify the relative pavement wear effects of different tyre types for the distress modes of fatigue cracking and secondary rutting. For permanent deformation in the bituminous layers (primary rutting), the ‘distress ratio’ (PWR_D) was chosen, as hardly any other data were available.

In principle, this means that these values cannot be combined, as they represent different concepts, and should be treated separately. As shown in the previous section, however, PWR_L and PWR_D values often can be rather similar.

4.3.8.3 Vehicle damage formula

Task Group 3 collected the available data into tables with PWR values, grouped by axle load, distress type, tyre type and inflation pressure. Table 4.9 gives an example of such a table.

Table 4.9 - Relative pavement wear effects, 90 kN axle (reference 12R22.5 dual) (Huhtala 1990)

Tyre size	Fitment	Pressure (kPa)	Thin pavement fatigue cracking	Medium pavement fatigue cracking	Thick pavement fatigue cracking
265/70R19.5	Dual	optimum	1.8	1.4	NA
12R22.5	Dual	optimum	1	1	1
385/65R22.5	wide single	optimum	3.7	2.7	NA
445/65R22. 5	wide single	optimum	2.8	2.3	NA

NA means data not available

These tables served as input data for a regression analysis. This aimed to produce a general formula to predict the relative damaging power of individual vehicles, as a function of several parameters, including tyre type, size and pressure. In the proposed formula, the damaging power of a vehicle is expressed in a number of standard axles. This number is called the VWF (Vehicle Wear Factor). The standard axle has air suspension, a reference load, a reference twin tyre assembly (with a reference inflation pressure, contact pressure, diameter, contact width etc.) having equal loads on both tyres. The proposed formulae are:

VWF = sum AxleWearFactor

AxleWearFactor = Tyre Configuration Factor * Axle Configuration Factor * Suspension Configuration Factor * Load Equivalency Factor

The Axle Configuration Factor (ACF) expresses the relative pavement wear of an axle load, when incorporated in a tandem axle or tri-axle configuration, relative to that same axle load when single (see 4.3.6.4). This was not explicitly investigated by TG3.

The Suspension Configuration Factor (SCF) expresses the relative pavement wear of an axle load with a certain suspension type, relative to an axle with a reference (air) suspension. This, too, was not explicitly investigated by TG3.

The Load Equivalency Factor (LEF) expresses the relative pavement wear of an axle load, as a function of the load size only (relative to a reference value). TG3 chose to adhere to the "power law" concept mostly used in pavement engineering, but to differentiate the exponent values between different distress modes: LEF= $(P_{actual}/P_{nominal})^n$, with n values of 1 to 2 for primary rutting, 4 for secondary rutting and 4 to 5 for fatigue cracking.

The Tyre Configuration Factor (TCF) is the essence of the TG3 research. It comprises influences of the tyre type (single / wide base / dual), inflation pressure (or differences from the optimum pressure for a given load), footprint width, footprint length, tyre diameter, tyre characteristics regarding dynamic force transmissibility, potential load imbalance (difference in load between the tyres of a dual tyre assembly), and influences from yet unknown factors. The format of this TCF will be detailed in section 4.5.10.

4.3.9 Conclusion: the research areas and questions

From the previous sections can be concluded what data are still lacking for a better understanding of the mechanism of the tyre/pavement interaction leading to pavement wear and the effect of the dominant tyre parameters. As was already indicated in section 4.2, the lacking data can be grouped into three fields:

- general information of tyre parameters for purpose of analysis and interpretation of the results,
- the behaviour of the tyre/pavement interaction under controlled conditions,
- the translation of the previous behaviour to real world conditions.

These three fields were translated into 11 specific questions to detail the necessary research.

The necessary general information of tyre parameters can be split up in :

1) What are average values of contact pressure and geometry of tyre/pavement contact area (length and width etc.), recommended inflation pressures, tyre diameters, tyre mass and spring stiffness etc?
2) What is the stress distribution in the tyre road contact area?

With respect to the behaviour of the tyre/pavement interaction under controlled conditions (tyre inflated as recommended, dual tyres equally loaded) information was needed on :

3) What is the relative effect of wide base singles and dual assemblies for equal inflation pressures (or equal size of contact areas) and equal loads?

4) What is the relative effect of tyre inflation pressure of the current tyres (varying in the range 7 - 9 bar in cold conditions) or size of contact area at equal load for wide base singles and dual assemblies?

5) What is the effect on pavement wear of possible future lower or higher tyre inflation pressures at equal load for wide base singles and dual assemblies?

6) What is the relative effect of tyre diameter (or the shape of the contact area) for wide base singles and dual assemblies for equal inflation pressures (or equal size of contact areas) and equal loads?

With respect to the translation to real world conditions information was required on :

7) What are the loading conditions in every days practice (including load sharing between the two tyres of dual assemblies and including inflation pressures)?

8) What is the influence on pavement wear of unequal load sharing between the two tyres in the case of a dual assembly?

9) What is the effect on pavement wear of under- and overinflation, at equal load, for wide base singles and dual assemblies?

10) What is the influence of wide base singles and dual assemblies on the dynamic interaction between vehicle and road surface?

11) What is the influence on pavement wear due to a change in tyre contact area in case of transverse unevenness of the road?

The questions 1) and 2) are treated in section 4.4, the questions 3) to 6) in section 4.1, and questions 7) to 11) in sections 4.6 and 4.7.

To answer these questions, a combination of research methods was chosen, consisting of:

- response measurements using test roads and Accelerated Load Testing facilities,
- performance measurements using Accelerated Load Testing (ALT) facilities,
- laboratory material testing,
- measurements of tyre – pavement contact stresses,
- numerical modelling.

This combination was chosen to combine the advantages of the individual methods (see Table 4.8), while evading some disadvantages. The choice was also influenced by time limitations and the availability of test methods to the participants of TG3.

It was realised that both numerical and experimental research had their limitations. Numerical modelling on the one hand is not yet able to fully describe all relevant aspects to general satisfaction. Experimental testing on the other hand can be largely troubled by inter-specimen variation. Especially in full scale experiments, where generally only one specimen (test pavement) is subjected to each test condition, this may influence comparative results.

4.3.10 Research program on pavement wear effects, designed for COST 334 TG3

Considerable research effort was specially initiated for COST 334 TG3. Table 4.10 lists the research program in the order of the research questions, mentioning the type of research, the country that made this contribution to COST 334, and the section number of this report where the research is described.

Table 4.10 - Summary of research, specially executed for COST 334 TG3

N°.	Parameters	Type of research	Country	Section
1	Tyre characteristics.	Survey Field measurements	ETRTO NL	4.4.2 4.4.5
2	Interface stress distribution	Measurements of tyre – pavement contact stresses	DE	4.4.9
3	Wide base single or dual assembly concepts.	Literature survey Rutting, ALT response + perform. tests Rutting, ALT performance tests Rutting, numerical modelling	NL UK NL PT	4.5.1 4.5.4 4.5.5 4.6
4	Tyre inflation pressure or size of contact area	Rutting, ALT response + perform. tests Rutting, ALT performance tests Rutting, numerical modelling	UK NL PT	4.5.4 4.5.5 4.6
5	Lower and higher inflation pressure	Rutting, numerical modelling Fatigue, ALT response tests + modelling	PT FR	4.6 4.5.6
6	Tyre diameter	Fatigue, ALT response tests + modelling	FR	4.5.6
7	Loading conditions	Field measurements.	NL	4.4.7
8	Unequal load sharing between the tyres of a dual assembly	Rutting, ALT response tests Fatigue, ALT response tests + modelling Rutting, numerical modelling Rutting + fatigue, numerical modelling	UK FR PT NL	4.6.3 4.6.4 4.6.5 4.6.6
9	Tyre underinflation or overinflation	Fatigue, ALT response tests + modelling	FR	4.5.6
10	Tyre road dynamic interaction	Full scale measurements using shaker table and test road	FI	4.7.3
11	Tyre road interaction transv. unevenness.	Numerical modelling	NL	4.6.6

4.4 TYRE DATA FROM PRACTICE

4.4.1 Introduction

To have realistic input data for pavement wear tests and tyre contact pressure measurements, it is necessary to know the loading conditions of heavy vehicles in everyday practice. The above question is not only related to wheel loads but includes the question of load sharing between the two tyres of dual assemblies and the influence of tyre inflation pressure on the pavement load. The relative effect of different tyre diameters on the shape of the tyre/road contact area (contact pressure in the footprint area) is a further question which should be looked at.

4.4.2 Tyre types to be considered

Based on present European sales, and on knowledge from the tyre industry on the development of new tyres, the following tyre types for heavy vehicles were determined as most relevant for main consideration in the work of Task Group 3:

Current ones :

385/65R22.5
295/80R22.5
315/80R22.5
12R22.5
215/75R17.5
12.00R20
11R22.5
10R22.5

Possible future ones :

315/70R22.5
295/60R22.5
385/55R19.5 and 385/55R22.5
445/45R19.5
495/45R22.5

Only radial ply tyres were considered, as these are almost exclusively used in Europe nowadays, whereas bias ply or diagonal ply tyres have become obsolete. Table 4.11 presents data on several properties of these tyres.

Table 4.11 – Properties of selected tyres (extracted from ETRTO standards manual 1997, except *, pending)

Tyre size designation		Measuring Rim width code.	Tyre dimensions (mm)						Load capacity per axle (kg)		Inflation pressure (bar)	Min. diam. of new tyres RE54 (mm)
			Design		Maximum in service.							
					Overall Width		Overall Diam.					
	Load indices		Section width	Overall diameter	Normal Road Service	Special Service	Normal Road Service	Special Service	Single	Dual		
385/65R22.5	160	11.75	389	1072	408		1092	1102	9000	/	9.0	1057
295/80R22.5	152/148	9.00	298	1044	313		1062	1072	7100	12600	8.5	1030
315/80R22.5	156/150	9.00	312	1076	318		1096	1106	8000	13400	8.5	1061
12R22.5	152/148	9.00	300	1084	309	315	1099	1110	7100	12600	8.5	1069
215/75R17.5	135/133	6.00	211	767	222		779		4360	8240	8.5	757
12.00R20 20PR	157/153	8.50	313	1122	319	319	1140	1153	8250	14600	9.0	1104
315/70R22.5	154/150	9.00	312	1014	318		1032	1040	7500	13400	9.0	1001
295/60R22.5	149/146	9.00	292	926	307		940	948	6500	12000	9.0	915
11R22.5	148/145	8.25	279	1050	287	293	1064	1074	6300	11600	8.5	1036
10R22.5	144/142	7.50	254	1020	262	267	1033	1042	5600	10600	8.5	1007
445/45R19.5	156	14.00	436	895	458		911	919	8000	/	9.0	883
495/45R22.5*	169	17.00	499	1018	524		1036	1044	11600	/	9.0	1005
385/55R22.5*	160	11.75	381	996	400		1012	1021	9000	/	9.0	983
385/55R19.5*	156	11.75	381	919	400		935	945	8000	/	9.0	906

4.4.3 Relevant tyre characteristics

4.4.3.1 General considerations

The tyre is the means by which a heavy goods vehicle transmits its load to the road over which it is travelling. The design and construction of tyres is an advanced technology in which a variety of modern techniques are employed in the design and manufacturing process. The ability of tyre manufacturers to understand the behaviour of the tyre has lead to considerable improvements in all aspects of the product in recent years, together with improvements in the materials of which they are made.

In use, the tyre is required to accept the applied loading, and to transmit this to the road surface in a way which ensures the safety of the vehicle, and a long service life of the tyre. Hitherto, there have been few considerations of the effects on the road surface of the tyre type used.

As a vehicle moves along a road, the load it applies to that road does not remain constant (as is indicated by the static weight of the vehicle) but is subject to changes that depend on a number of conditions, principally the longitudinal profile of the road surface. the speed of the vehicle and the type of suspension used on the axle in question. The degree of so-called dynamic loading is expressed as the Dynamic Load Coefficient, which can be as much as 1.4 to1.5 in the worst cases. This means that a static load of 10 tonnes on the axle can on occasions weigh 14 to15 tonnes when in motion.

A second feature of the loading of the pavement that is relevant to the performance and behaviour of the tyre is the frequencies at which such dynamic loading takes place. The DIVINE project, among a number of others, has shown that the two principal modes of vibration of a vehicle are the body bounce mode, occurring at approximately 1.5 to 3.5 Hz and the axle hop mode, occurring at 10 to 15 Hz.

In general terms, it is considered that there are four tyre properties that are particularly relevant to road loading and wear, and these are contact area (footprint), out-of-roundness (circularity), manufacturing tolerance on diameter, and inflation pressure. Clearly there are other characteristics of the tyre that are strongly related to these, and which may influence the load applied to the road. These will include, for example, tyre design, tread pattern, etc.

4.4.3.2 Contact area

Contact area is an important consideration from the point of view of pavement design. Inputs to mechanistic models of design require the shape of the loaded area to be defined, and this is generally assumed to be circular. More advanced models, capable of accepting different areas, are now available, but are not yet commonly used in pavement design methods.

The footprint of the tyre is the area enclosed by the boundary of the contact between tyre and road. For the tyres of greatest interest in Europe, namely those having radial ply construction, the footprint is a function of load and inflation pressure. Again in very general terms, increases in load, while maintaining the inflation pressure, will result in a lengthening of the contact area. For radial tyres, this area is nearly rectangular in shape, unless the tyre is lightly loaded or severely overinflated. There is also some change in the width of the footprint, but this is very small compared with the lengthening that takes place (except for lightly loaded or overinflated tyres).

There is a (sometimes) significant difference between the exact contact area, which will take into account the effect of the tread pattern, and the assumed contact area (the area enclosed by the boundary of contact. Little work has been published on this topic, but there is some evidence that the difference between these two figures can be 20% or more. If this figure were common, then there would be a need to include such variations in any pavement design method calculations, because of its effect on the calculation of contact pressure.

Not only the size of the contact area is important, but also its shape. There will be differences in stresses in the pavement between e.g. a wide and short contact area, a square area, a circular area, or a narrow and long area (all having equal area size and vertical contact stress). Therefore, the distance between the tyres of a dual assembly (and the absence of such distance for a wide base single) will also influence the stresses in the pavement, as this distance widens the area over which the load is distributed.

Huhtala et al (1997) have also commented on the role of uneven distribution of contact pressure, particularly in respect of the response of thin pavements to tyre loads, and further work aimed at understanding the behaviour of thin pavements under loads will need to be undertaken.

4.4.3.3 Inflation pressure

The question of contact area and contact pressure cannot be separated from that of inflation pressure, and there are two aspects of the relationship that perhaps need further investigation.

It is often assumed that the contact pressure between tyre and road is equal to the inflation pressure of the tyre. This was frequently shown not to be the case (a.o. De Beer et al 1996, Blab 1999). In the dynamic condition, when the tyre is subject to a continuously varying load, this may be even more incorrect.

There is some evidence to suggest that in twin wheel assemblies, lack of maintenance leads to unequal tyre pressures in each tyre of the assembly. In extreme cases, the difference in tyre pressures may lead to a situation in which the lowest pressure tyre (usually the inner) is doing little or nothing to support the load on the assembly.

It is believed that the first of these will need theoretical investigation, while experimental surveys will be required to provide further information on the latter. At present, however, it would appear that some automatic control of tyre pressure on the vehicle would be desirable, and COST 334 may need to consider this possibility very carefully.

4.4.3.4 Size tolerance

ETRTO have informed COST 334 that the manufacturing tolerance and the difference in tread depth from new to partially worn (in case of traction tread type) on diameter of truck tyres may be ± 1 to 1.5%. (This is the tolerance between manufacturers for the same size indication. The manufacturing tolerance for one tyre type of one manufacturer is generally much smaller.) Assuming a tyre diameter of 1 metre, and taking the worst case on tolerance, leads to the theoretical possibility that two otherwise identical tyres may differ in diameter by as much as 30 mm. If fitted to a dual tyre assembly, the load distribution between tyres would clearly be unequal, because the contact areas and pressures would be affected. It is not clear whether this is a phenomenon that occurs sufficiently frequently to be of concern.

4.4.3.5 Out-of-roundness (circularity)

Recently, Jacob et al. (1997) have determined experimentally that a peak in the Power Spectral Density (PSD) curve of dynamic vehicle loading occurred at the frequency of rotation of the tyres, and deduced that the size of the peak was a function of the out-of-roundness of the tyre. Although the magnitude of such loadings is relatively small compared to other dynamic factors, it may be necessary to consider the phenomenon in the context of COST 334 for the following reason.

In a twin tyre assembly, it is conceivable that the tyres might be mounted in such a way that the out-of-balance forces from each tyre either reinforce each other, or cancel each other. In the case of the wide single wheel, any out-of-balance force will add to the normal dynamic loading situation.

4.4.4 Tyre – pavement contact area (tyre footprint) values in practice

For the bias ply tyres of old, the contact area between the tyre and the pavement (the tyre footprint) was circular or elliptical. For present-day radial tyres, the footprint is rather rectangular when tyre load and inflation pressure are well matched. The footprint width generally equals the tread width (except for strongly overinflated or ‘under-loaded’ conditions, when the footprint width may be less than the tread width). The footprint length for a certain tyre type (at constant size, manufacturer, diameter, structure) is rather constant for matching combinations of load and pressure. At overloading (or ‘under-inflation’), the footprint length generally increases, more at the edges than in the middle. At overinflation (or ‘under-loading’), the footprint length generally decreases, again more at the edges than in the middle, resulting in a more elliptical shape.

In this report, the term ‘footprint area’ indicates the entire area within the footprint perimeter (the ‘gross contact area’), i.e. both the area of the tread grooves (sipes) and the ‘net contact area’ between tyre rubber and pavement. The tread pattern (and the relative sipe area) may be different for steering, driven and towed axles, and may also differ between different tyres of the same nominal size.

Table 4.12 to Table 4.16 give information from various sources on footprint size for several tyre types. Please note that substantial differences may occur between tyres of the same nominal size but of different manufacturers or even of different types (structure, tread pattern, materials) for the same manufacturer. Due to constant development, these values may also change over the years. Differences between the given values may also be due to differences in measurement methods between authors, or to measurement variability.

Table 4.12 - Tyre footprint size of some Michelin tyres (Penant 2000b)

Tyre size	Fitment	Load per tyre (kg)	P (bar)	Width [1] (mm)	Length [1] (mm)	Area [1] (cm²)
295/60R22.5	dual	2250	8	258	155	399
295/60R22.5	dual	2875	10	259	165	427
295/80R22.5	dual	2250	7	243	170	413
315/80R22.5	dual	2250	6.5	253	179	453
315/80R22.5	dual	2875	8	253	193	490
385/65R22.5	single	4500	10	284	202	574
385/65R22.5 Energy	single	4500	10	302	193	583
495/45R22.5	single	4500	8	425	161	686
495/45R22.5	single	5750	10	426	173	737

[1] Width and length values are averaged over the contact area envelope, so Area = width*length

Table 4.13 - Tyre footprint size of some Michelin tyres (Theis 2000)

Tyre size	Fitment	Load per tyre (kg)	Inflation pressure (bar)	Max. width [1] (mm)	Max. length [1] (mm)	Gross area [1] (cm²)	Net contact area (cm²)	Net/gross area (%)
295/60R22.5	dual	2875	9.5	258	205	472	309	65.5
315/80R22.5	dual	2875	7.5	258	247	532	351	66.1
385/65R22.5	single	4500	9.5	283	232	579	415	71.7
385/65R22.5	single	5750	9.5	283	256	681	505	74.1
495/45R22.5	single	5750	9.5	427	213	709	535	75.4

[1] NB! Gross contact area or footprint area is considerably smaller than max.width*max.length, mainly due to strongly irregular footprint length

Table 4.14 - Footprint width or tread width of some tyres (Groenendijk 1999)

Tyre size	Fitment	Manufacturer	Footprint width or tread width (*) (mm)	Footprint width / section width (%)	Reference
10R20	dual	unspecified	179-183	71	Sharp et al. (1986)
10R22.5	dual	Michelin	186	73	Gramsammer et al. (1998)
11R22.5	dual	Michelin	200 (*)	72	Sharp et al. (1986)
11R22.5	dual	Goodyear	222 (*)	79	Sharp et al. (1986)
12R20	dual	Bridgestone	210	69	Bouman et al (1991)
12R22.5	dual	unspecified	180 – 190	61	Krarup (1994a)
295/60R22.5	dual	Michelin	260 (*)	88	Groenendijk (1999)
315/80R22.5	dual	Michelin	260 (*)	82	Groenendijk (1999)
15R22.5	single	unspecified	283 – 285	75	Sharp et al. (1986)
15R22.5	single	Sumitomo	290 – 295 (*)	77	Sharp et al. (1986)
385/65R22.5	single	unspecified	280 – 290	74	Krarup (1994a)
385/65R22.5	single	Michelin	287 (*)	74	Groenendijk (1999)
16.5R22.5	single	Bridgestone	315 – 320 (*)	76	Sharp et al. (1986)
425/65R22.5	single	Bridgestone	295 – 305	70	Mante et al. (1995a)
445/65R22.5	single	unspecified	330 – 340	75	Krarup (1994a)
18R22.5	single	Goodyear	345 – 350 (*)	76	Sharp et al. (1986)
495/45R22.5	single	Michelin	425 – 430	87	Gramsammer et al. (1998)

Measured tread width data are indicated by (*), other data are measured footprint widths

Table 4.15 - Tyre footprint size for steering axles (ETRTO 2000 [1])

Axle load in tonnes ==>				6		7		8	
Tyre size	Fitment	Contact area width	Diameter	Contact area	Tyre press.	Contact area	Tyre press.	Contact area	Tyre press.
		mm	mm	cm²	kPa	cm²	kPa	cm²	kPa
295/60R22.5	single	244	924	439	925				
295/80R22.5	single	235	1059	495	800	504	950		
315/70R22.5	single	253	1024	502	800	512	950		
315/80R22.5	single	247	1085	537	700	548	825	559	950
385/55R22.5	single	329	998	525	650	535	775	544	900
385/65R22.5	single	285	1071	546	650	555	775	564	900

[1] The combinations of axle/tyre/load were chosen by TG3 and do not constitute ETRTO recommendations for use

Table 4.16 - Tyre footprint size for driven and towed axles (ETRTO 2000 [1])

Axle load in tonnes ==>				7		8		9		10		11.5		13	
tyre size	fit-ment	cont. area width	dia-meter	cont. area	tyre pres.	cont. area	tyre pres.	cont. area	tyre pres.	cont. area	tyre pres.	cont. area	tyre pres.	cont. area	tyre pres.
		mm	mm	cm²	kPa	cm²	kPa	cm²	kPa	cm²	kPa	cm²	kPa	cm²	kPa
265/70R19.5	dual	210	872	347	650	354	750	360	850	365	950				
295/60R22.5	dual	244	924			409	650	413	750	422	825	427	975		
295/80R22.5	dual	235	1059			455	600	465	675	473	750	482	875		
315/70R22.5	dual	253	1024			496	575	505	650	513	725	521	850		
315/80R22.5	dual	247	1085			467	550	475	625	482	700	488	825	500	925
10R22.5	dual	186	1017	365	625	377	700	381	800	386	900				
11R22.5	dual	184	1054			385	650	395	725	397	825	407	950		
11.00R20	dual	207	1086	449	525	460	600	461	700	470	775				
12.00R20	dual	225	1132			505	550	513	625	520	700	527	825	540	925
12R22.5	dual	201	1085			430	600	439	675	447	750	454	875		
385/55R22.5	single	329	998	534	775	542	900								
385/65R22.5	single	285	1071	555	775	564	900	578	1000						
425/65R22.5	single	308	1126	663	625	674	725	693	800	702	900				
445/65R22.5	single	340	1155	720	600	742	675	749	775	767	850				
495/45R22.5	single	427	1013			707	675	715	775	732	850	742	1000		

[1] The combinations of axle/tyre/load were chosen by TG3 and do not constitute ETRTO recommendations for use

As stated above, values may vary over the years, and variations may occur between manufacturers and even between different tyre types of the same size designation for the same manufacturer. The data in Table 4.15 and Table 4.16 are ‘average values’ over several manufacturers and over several years, representative of the European truck fleet in 2000. The values of contact areas are for individual tyres, not dual assemblies. These contact area values are those chosen for tread patterns corresponding to the representative use. The tread patterns may be different from a tyre size to an other. In consequence, from the table, the contact areas of the different tyre sizes must not be compared too strictly. The pressures in Table 4.15 and Table 4.16 are values for operating conditions, i.e. ‘hot’. (These were computed by adding 1 bar to the recommended ‘cold’ pressures.) The pressures were rounded at the superior quarter of bar.

4.4.5 Tyre inflation pressures in practice (UK, DE, NL) and manufacturer’s recommendations

In Great Britain the tyre inflation pressure of 1322 trucks, tractors and semitrailers was checked (Addis 1998). The data of four different checkpoints in the road network were averaged. The tyre inflation pressure values were differentiated according the different axles: steering axle, drive axle (inner and outer side of twin tyre assembly), second or towed (lift-) axle on truck or tractor, twin assembly on towed semitrailer axle, (wide base) single tyres on towed semitrailer axle. Because the survey was focused on heavy trucks the values of single trucks with only two axles were excluded.

The following results were obtained:

- Steering axle tyres (n = 1560): average pressure: 8.47 bar
- Drive axle, twin tyres, outside (n = 1827): average pressure: 7.20 bar

- Drive axle, twin tyres, inside (n = 945): average pressure: 7.14 bar (Note: The inner tyre inflation pressure could often (50%) not be checked because of a missing valve extension. This might bias the observations, as the unchecked tyres could be improperly inflated, just because of the missing valve extension.)
- Towed truck or tractor single tyres (n = 374): average pressure: 7.66 bar
- Semitrailer (wide base) single tyres, average of all 3 axles (n = 3004): average pressure: 8.57 bar
- Semitrailer, twin tyres, average inner and outer tyre (n = 1131): average pressure: 7.0 bar

It was interesting to note that the tyre inflation pressure was much too high for the steering axle at which a pressure of about 6 to 7 bar would be correct for an axle load of 6 to 7 tons. This is done by truckers to ease steering manoeuvres. For the other axles the inflation pressure seemed to be correct in most cases (average values). Twin tyres on the semitrailer axles have lower pressure than wide base singles.

The UK statistics can not be used to look at the differences between inner and outer tyres of twin assemblies (only average values), but the German study of Stanzel et al (1996), can be taken to answer this question. It can be seen that the differences in inflation pressure between both tyres are low. (However, as the examined truck fleet was under supervision of a tyre manufacturer, its tyre maintenance could have been very strict and not representative. Therefore, the differences in inflation pressures in practice could be larger.)

For the twin tyres of the (first) drive axle of big trucks in 93.5% of the cases the inflation pressure of the inner tyre is within the range of ± 10% of the inflation pressure of the outer tyre. More detailed values are:

- 43% have exactly the same inflation pressure,
- 67% lie in the range of ± 2%,
- 82% lie in the range of ± 4%
- 89% lie in the range of ± 6%.

Mean tyre inflation pressures - and coefficients of variation - for the different tyre positions on trucks (without trailers) are as follows (Stanzel et al 1996):

- steering axle tyres left (n = 320): 7.92 bar +/-7.2%
- steering axle tyres right (n = 322): 7.93 bar +/-8.7%
- first drive axle tyres left outside (n = 311): 7.4 bar +/-9.6%
- first drive axle tyres left inside (n = 309): 7.95 bar +/-8.6%
- first drive axle tyres right outside (n = 316): 7.48 bar +/-8.3%
- first drive axle tyres right inside (n = 281): 7.38 bar +/-11.6%
- second drive axle (or lift axle) tyres left outside (n = 67): 7.69 bar +/-10.4%
- second drive axle tyres left inside (n = 45): 7.37 bar +/-8.2%
- second drive axle (or lift axle) tyres right outside (n = 63): 7.73 bar +/-9.1%
- second drive axle tyres right inside (n = 40): 7.41 bar +/- 4.6%

Tyre inflation pressures of twin tyres on drive axles (n =222) and the differences between inner and outer tyres were also examined for NL, see 4.4.7 (Nieuwsma 1999). The pressure values (measured while warm) of the drive axle twin tyres range from 8 to 9 bar. These values are considerably higher than in the studies mentioned above. This may be due to the tyres being warm while measured, but also may reflect the fact that many drive axles in this study were overloaded, which is often combined with overinflation by the truck drivers. The differences in inflation pressures between inner and outer tyres on drive axles is in 71% of the cases in the range +/-3% and in 91% of the cases in the range of +/-9%. These values are in line with the values from Stanzel et al (1996). Figure 4.18 shows the results of the tyre inflation pressure data for the drive axles with dual tyres.

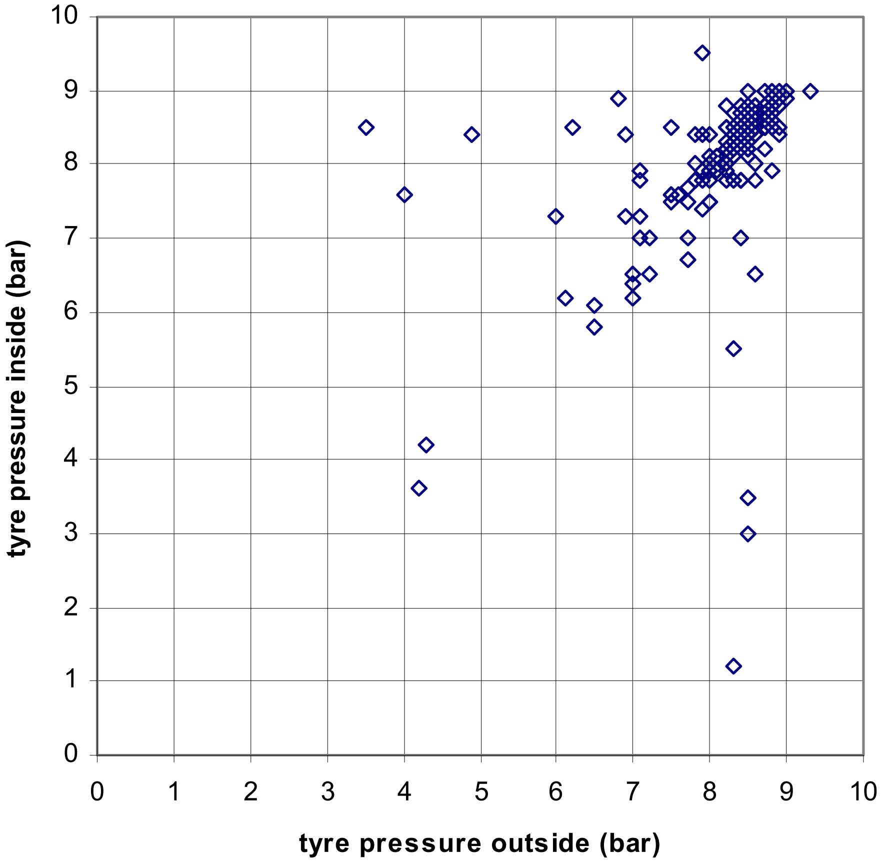

Figure 4.18 - Tyre pressure of twin tyres, drive axle, (n=222) (Nieuwsma 1999)

Information of tyre traders and service stations leads to the same conclusion, namely that tyre service and inflation pressure checks are quite good for trucks in long distance transports (but not so good for trucks operating in short distance transport, e.g. transport of bulk goods for building sites).

In the tyre pressure surveys mentioned above, no distinction was made between the different tyre sizes. However, different tyre sizes have different manufacturer's recommendations for inflation pressure (as a function of the wheel load). This is shown in Figure 4.19 and Figure 4.20, which give data for several current tyre sizes for road use. (These data may vary between tyre manufacturers.). The graphs are sorted by tyre rim diameter. (Note that the outer diameter of a tyre is not only influenced by its rim diameter, but also by its aspect ratio, see 4.3.2.5. So equal rim diameter does not imply equal tyre diameter, nor vice versa. However, generally tyres with larger rim diameters will also have larger outer diameters.)

The graphs show that a decrease in tyre diameter generally corresponds with an increase in recommended tyre inflation pressure for the same axle loads. The graphs also show that, for a given rim diameter, the wide base single tyres generally have higher recommended tyre inflation pressure for the same axle loads than dual tyres.

Recent roadside surveys showed that the tyre inflation pressures of dual tyres were generally lower than those of wide base single tyres. However, the axle loads were different. Over the last thirty years tyre pressures have been increasing, but higher tyre inflation pressures have been used in wide singles when compared to dual tyres. This has occurred due to tyre design and existing standards. At present wide single tyres have slightly higher pressures. However, from the design point of view there is no reason why wide single or dual tyres cannot have the same inflation pressure for the same load.

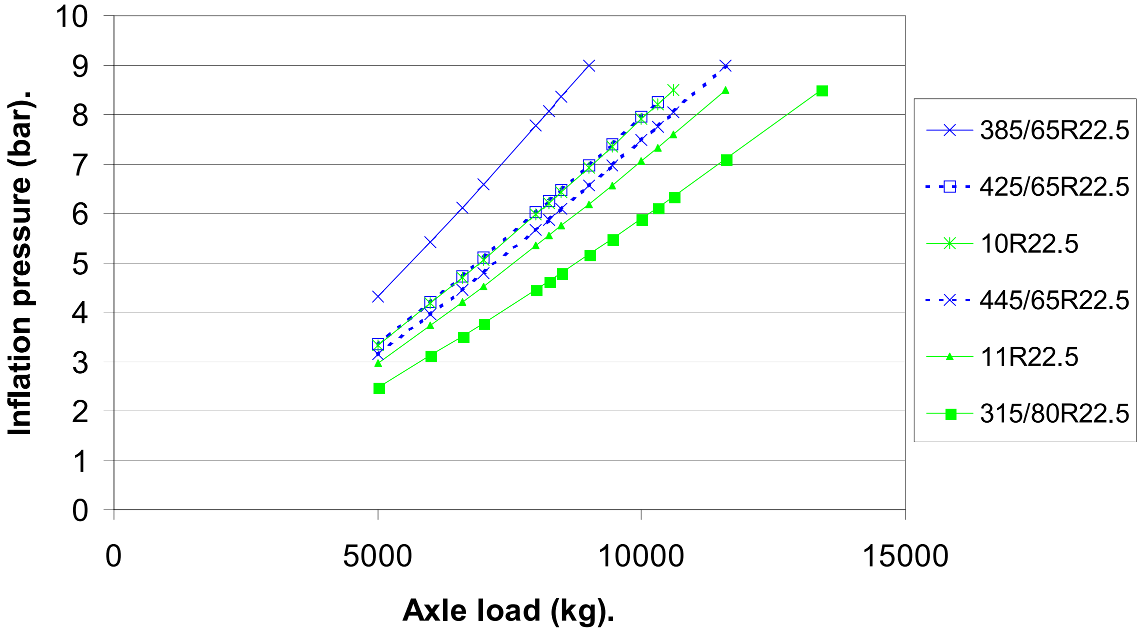

Figure 4.19- Recommended tyre inflation pressure vs axle load, towed axles, R22.5 tyre sizes

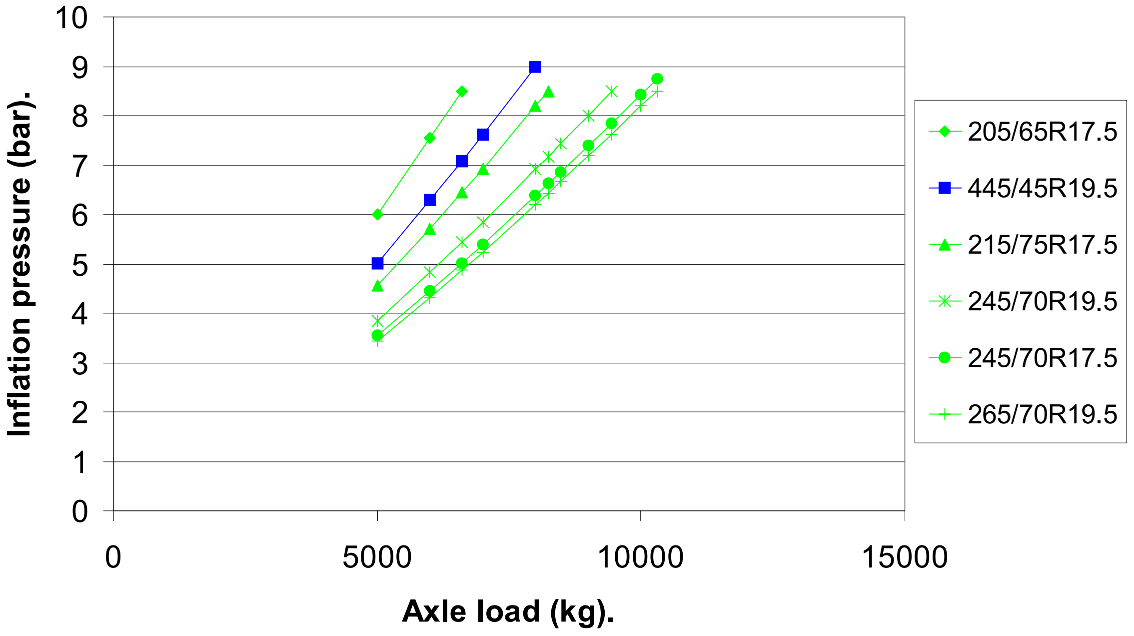

Figure 4.20 - Recommended tyre inflation pressure vs axle load, towed axles, R17.5 and R19.5 tyre sizes

4.4.6 Profile depths in practice (DE, NL)

Differences in the circumferences of the tyres of twin assemblies, e.g. new tyre and regrooved tyre in one assembly, do not normally exist, because twin tyres mostly are changed both at the same time. If there is one tyre defect, both tyres are changed and the used tyre without a defect becomes a spare tyre. (However, this ‘ideal’ situation might be less common outside Germany, especially for smaller fleets of trucks.)

The profile depths of twin tyres on drive axles were measured by Stanzel et al (1996) (n = 646 twins) and Nieuwsma (1999) (n = 292 twins). In 88.5% of the cases the profile depth difference is smaller than +/-2 mm (Stanzel et al 1996). This is in line with the value of 88% in the range of +/-2.25 mm in Nieuwsma (1999). An average value of 10.8 mm profile depth, which means roughly half of the profile depth of a new tyre, is given for the inner and outer tyre of twin assemblies in Nieuwsma (1999).

4.4.7 Unequal load sharing of twinned wheels in practice (NL) and experiment

Wheel load measurements were executed in the Netherlands as a Dutch contribution to COST 334 (Nieuwsma 1999). Figure 4.21 shows the measurement setup, enabling independent weighing of the individual tyre loads. Results are shown in Figure 4.22 and Figure 4.23.[4]

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[4] This figure shows a considerable number of cases of overloading of wheel loads for the drive axles of trucks and tractors. Each of the four wheels of the 11.5 t drive axle should not carry more than 2.875 t. The trucks for this survey were selected by police officials, who probably have concentrated on potentially overloaded vehicles.

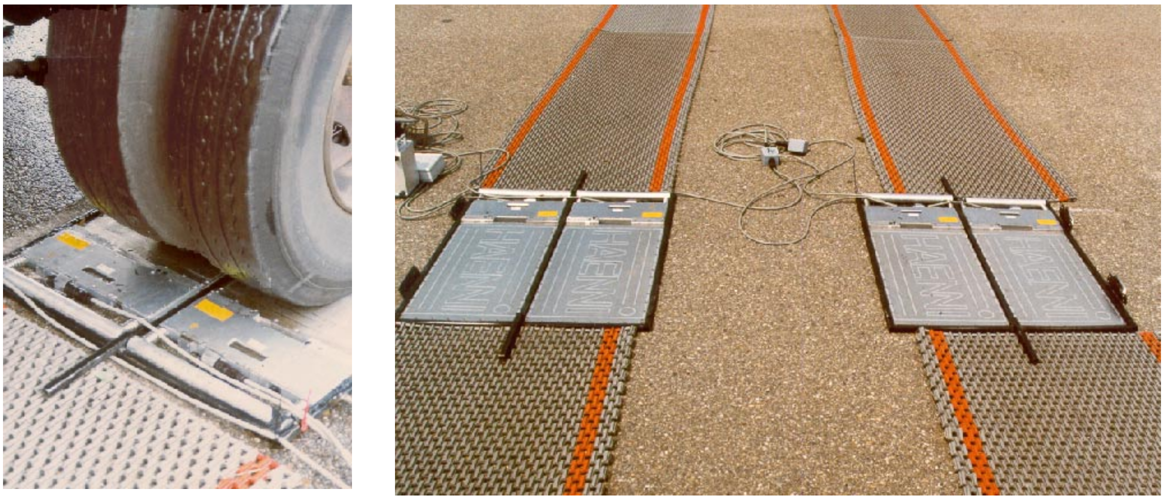


Figure 4.21- Setup for wheel load measurements (Nieuwsma 1999)

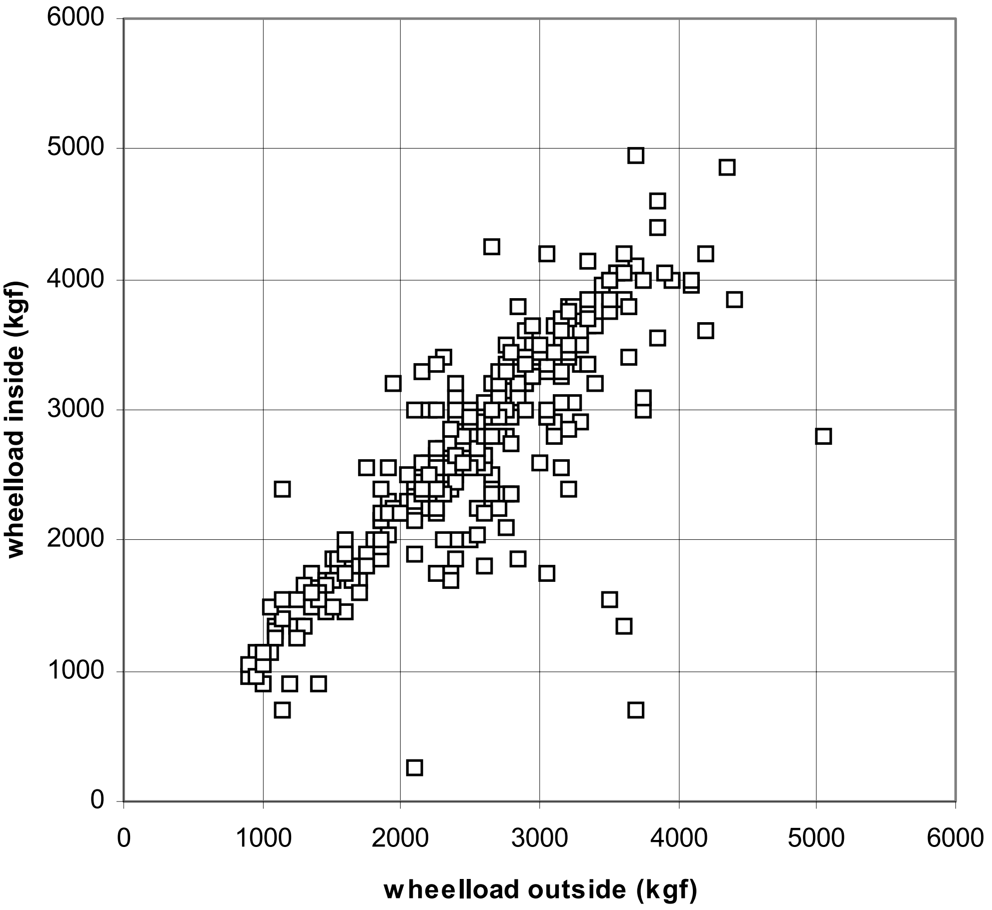


Figure 4.22 - Wheel loads of twin tyre assemblies, drive axle (n = 297) (Nieuwsma 1999)

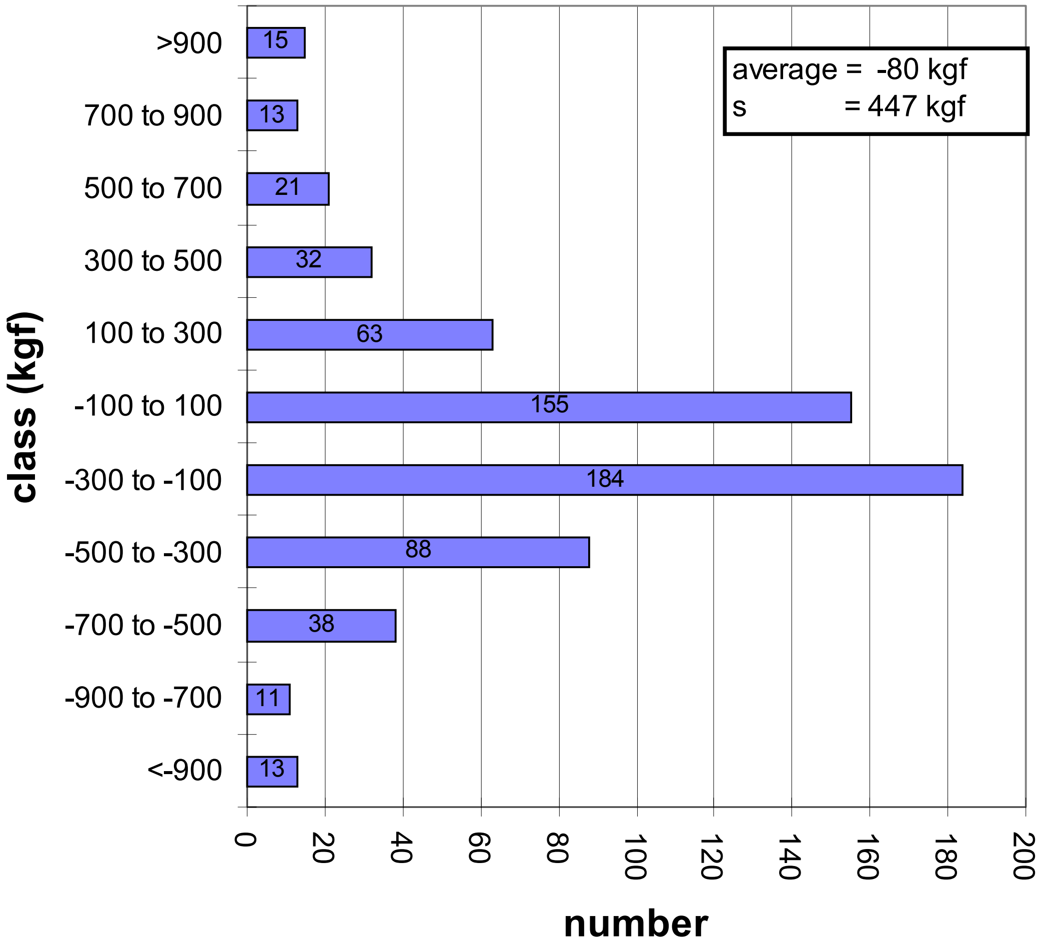


Figure 4.23 - Difference between outer and inner wheel load of dual tyre assemblies, driven and towed axles (n=633) (Nieuwsma 1999)

For drive axles, the inner tyre of a dual assembly had on average about 200 kg more load than the outer tyre. Knowing the average loading of a dual assembly is about 5000 kg, the inner tyre carries 52% and the outer tyre 48%. In about 20% of the cases the difference is more than +/- half a ton (n = 297). In 17% of the cases there is an equal load share (+/-100 kg). In 67% the outer tyres are less loaded than the inner tyres and in only 16% the outer tyres are more heavily loaded than the inner tyres. A possible explanation could be the bending of the axle under load.

For towed axles of trailers and semitrailers, on average both tyres carry equal loads.

Table 4.17 shows calculated data on the unequal load division of some twinned tyres, which result from differences in tyre diameter of 10 mm. Such differences could partly be due to manufacturing tolerances, but are mainly caused by differences in tyre wear.

Table 4.17 – Unequal load division between twinned tyres in case of 10 mm difference in diameter (Penant, 1999)

Tyre size	Cold inflation pressure (bar)	New tyre diameter (mm)	Partially worn tyre diameter (mm)	Equilibrium load division new tyre – worn tyre (kg)
315/80R22.5	7.1	1076	1066	3000 - 2750
11R22.5	8	1064	1054	3015 - 2735
315/70R22.5	7.5	1016	1006	3025 - 2725
295/60R22.5	8.5	929	919	3050 - 2700

4.4.8 Influence of tyre type on dynamic wheel loads

One research question was whether differences in tyre type would influence the dynamic component of the wheel loads in practice.

Neddenriep (1996) showed results of measurement of dynamic contact forces and related parameters on a 385/65R22.5 wide base single tyre and on twinned 295/75R22.5 tyres. These measurements were carried out on three different test tracks with a special testing device installed on a heavy vehicle. The author explained that "Especially for higher speed levels" (60 and 80 km/h) "the wide base single tyres show results on a lower level than twins for all measured dimensions". The difference may be very small, but it is an important fact that the single is not worse, and even slightly better, in terms of dynamic contact force, on asphalt and Belgian blocks roadways.

Tielking (1993, 1994) compared a single 425/65R22.5 and two 11R22.5 tyres on an MTS servo-hydraulic machine. He explained that "except near the resonant frequency, the transmissibility of the wide base tyre is less than that of the dual tyres. At 10 Hz, which is near the fundamental vibration frequency of a heavy highway vehicle, the force transmissibility of the wide base is measured at 35% less than that of the dual tyres. This indicates that the dynamic component of pavement load from a wide base tyre will be less than the dynamic component of pavement load from dual tyres." (Tielking 1994) Moreover, Tielking (1993) showed that truck tyre force transmissibility has a negligible sensitivity to the load level and a slight sensitivity to inflation pressure. This strengthens the preceding conclusion.

Similar results were found in a shaker table study by Streit et al (1998). Two different types of dual tyres (standard and low profile) were compared with a wide base tyre. The magnitudes of the dynamic wheel loads produced by the dual tyres were very similar. The Dynamic Load Coefficient (DLC, = standard deviation of tyre load / mean value) values of the standard radial tyres were about 2% higher than those produced by the low-profile tyre. The wide base tyre produced DLC’s of 10 to 12 % lower than those of the dual tyres.

Further tests were executed at the Finnish VTT, and are described in section 4.7.3.

4.4.9 Measured contact pressures (DE)

4.4.9.1 Introduction

Within the framework of COST 334 TG3, measurements of contact stresses in the tyre - pavement interface were executed. This research was part of the German contribution to COST 334 TG3.

4.4.9.2 Fuji- Foil Measurements

One possibility to measure the contact pressure of a tyre on the road surface is the so-called Fuji- Foil measurement. The contact pressure in the tyre footprint can only be measured statically with this method. Two Foils are placed on top of a sheet metal plate under the lifted tyre. One foil has microscopic small bubbles filled with red „ink“, the other foil, the so-called developer foil, acts as „blotting paper“. After subjecting the foils to the known tyre load, different contact pressures can be seen on the developer foil as areas of different shades of red colour. The footprints measured in this manner can be analysed by a Fuji Scanner, which changes the red colour to different colours ranging from blue for low pressure to red for high pressure (like in a thermography measurement). The colours can be scaled, if the wheel load is known.

Figure 4.24 and Figure 4.25 show as examples the contact pressure of a 315/80R22.5 tyre on the front axle of a truck with a wheel load of 2.5 t and an (overinflated) tyre inflation pressure of 8.3 bar, (correct inflation pressure for this wheel load would be 5 bar). Figure 4.24 shows the original developer foil, Figure 4.25 shows the scanned foil.

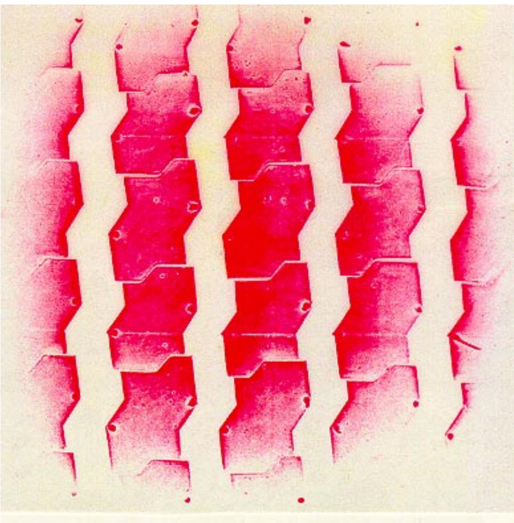


Figure 4.24 - Footprint measured with Fuji Foil, wheel load 2.5 t, 8.3 bar, 315/80R22.5

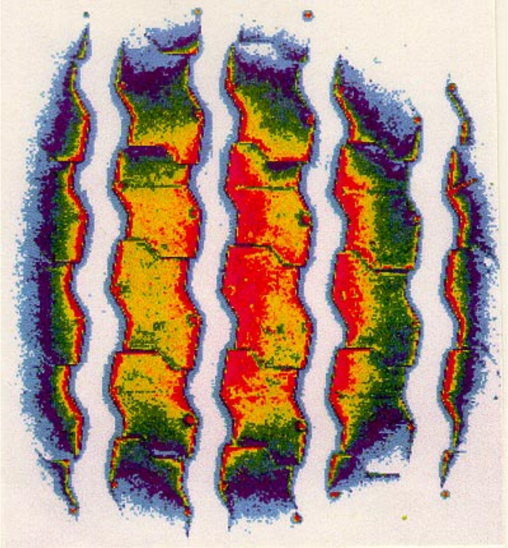


Figure 4.25 - Footprint, same tyre as in figure 4.24, scanned Fuji Foil

4.4.9.3 Tekscan Measurements

The Tekscan contact pressure measuring system consists of 9152 pressure sensors, each 0.5 cm x 0.5 cm, in a 0.3 mm thick foil. The electrical resistance of each sensor changes as load is applied. The size of the foil is 45 cm x 50 cm. It is possible to make static load measurements and dynamic load measurements on running trucks as well, because every measuring channel is read by the PCM system 127 times a second. A truck travelling at 80 km/h produces at least one full footprint in the computer memory which can be analysed afterwards. Figure 4.26 shows the BASt tractor-semitrailer unit on the Tekscan system, which was fixed on a sheet metal plate and covered with a Teflon foil to avoid damage. Tests were made at 80 km/h on a blocked highway lay-by.

Figure 4.26 - BASt tractor-semitrailer unit during dynamic footprint measurement at 80 km/h

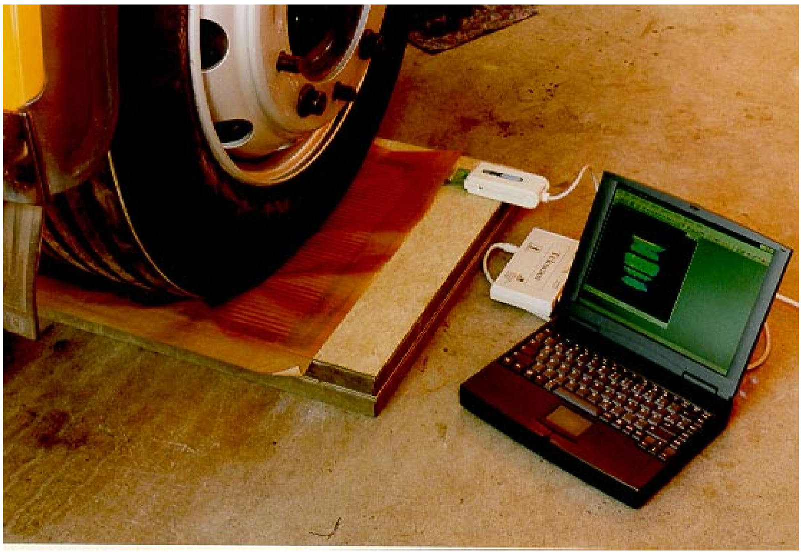


Figure 4.27 - BASt tractor-semitrailer unit on the Tekscan system, static footprint measurement, test with smaller tyre diameter and plates for levelling the truck

Figure 4.28 shows a footprint for a truck tyre measured statically with the Tekscan system and Figure 4.29 shows a footprint at 80 km/h. The colours are not scaled in the same way as in the Fuji foil, so no direct comparison is possible. The rolling tyre shows a „longer“ footprint. The footprints were produced by the sensor mat described above, but the resolution is not sufficient. So it is not possible to get more detailed information about local contact pressure. Sensor mats with smaller (but more) pressure sensors, to identify better the tread grooves were not available.

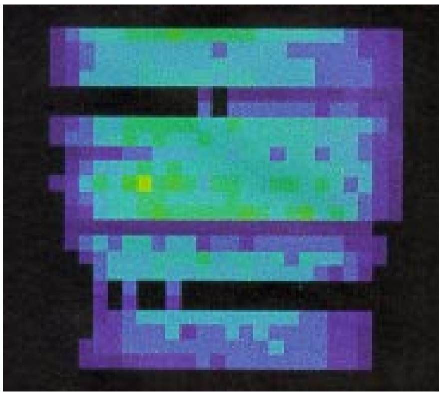


Figure 4.28 - Static footprint of a truck tyre

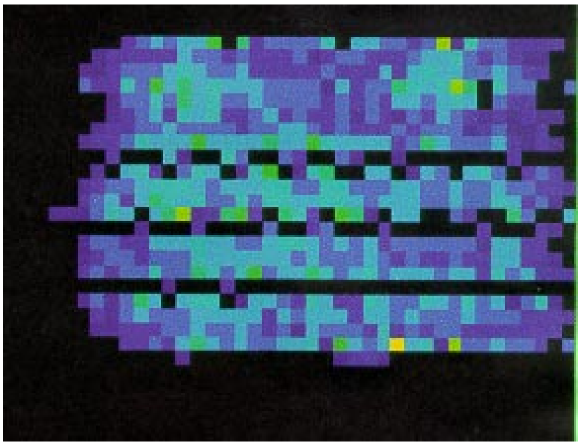


Figure 4.29 - Footprint of a truck tyre at 80 km/h

Beside the above-mentioned difference in the length of the footprint in the dynamic test the maximum load is a little bit further forward than in the static footprint, but static measurements seem to be sufficient to analyse contact pressures under various loading conditions. So the following footprints were made with the Fuji Foil.

4.4.9.4 Footprint measurements of the tyres used in the Lintrack test program

The following footprints of several Michelin tyres were made in NL during the Lintrack test program, described in 4.5.5, and analysed in DE. The footprints are recorded with a two component Fuji-Foil as discribed in section 4.4.9.2. Table 4.18 shows the conditions under which these static footprints were recorded.

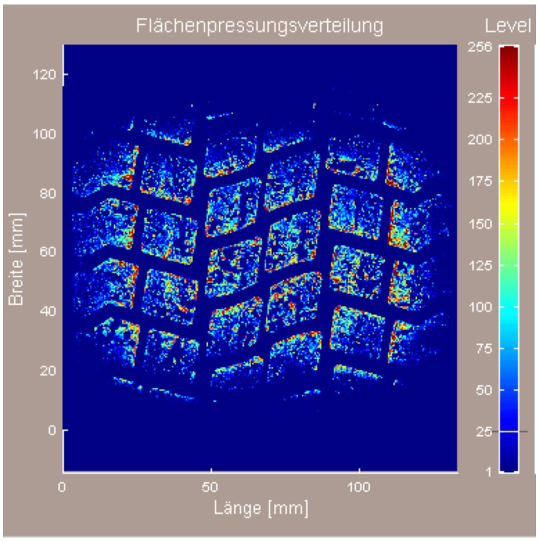


Figure 4.30 - 295/60R22.5 left

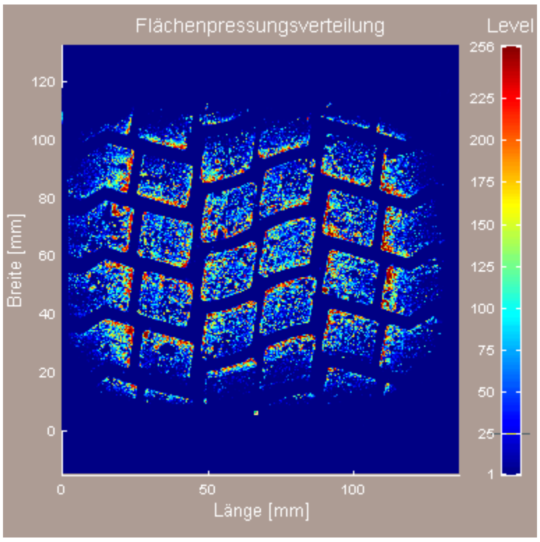


Figure 4.31 - 295/60R22.5 right

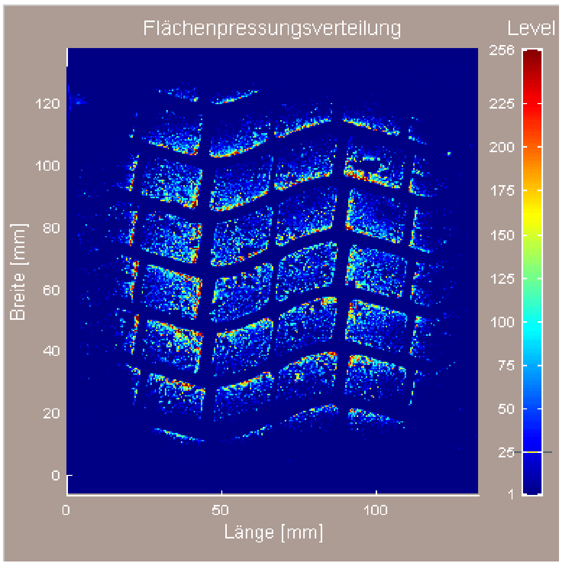


Figure 4.32 - 315/80R22.5 left

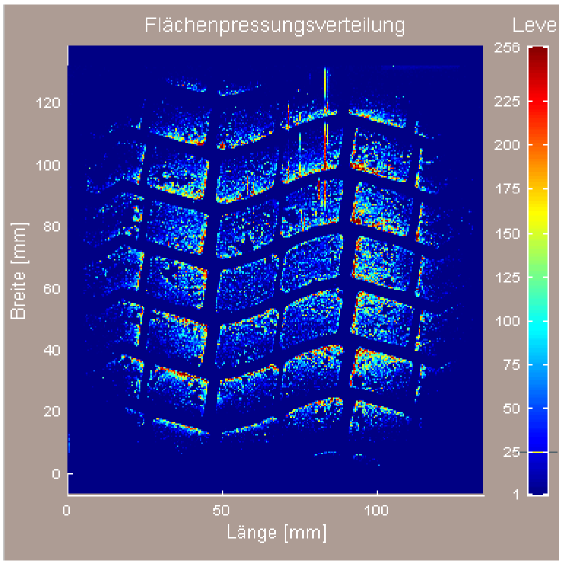


Figure 4.33 - 315/80R22.5 right

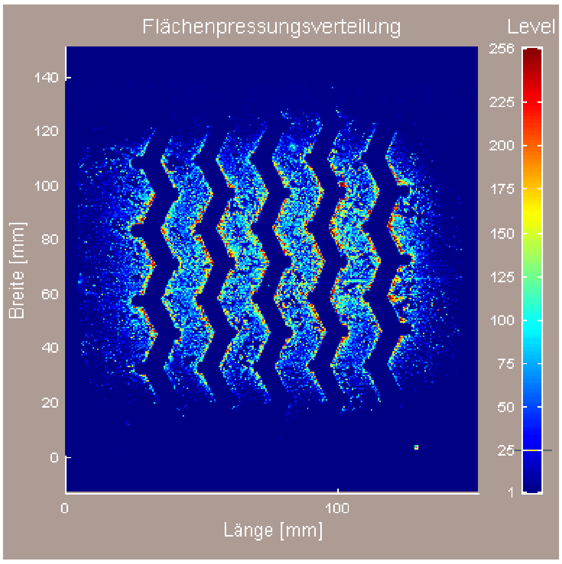


Figure 4.34 - 385/65R22.5, 45 kN, 9.5 bar

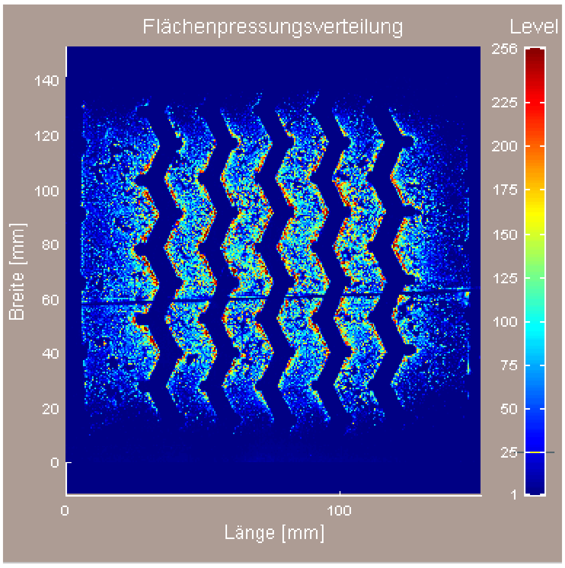


Figure 4.35 - 385/65R22.5, 57.5 kN, 9.5 bar

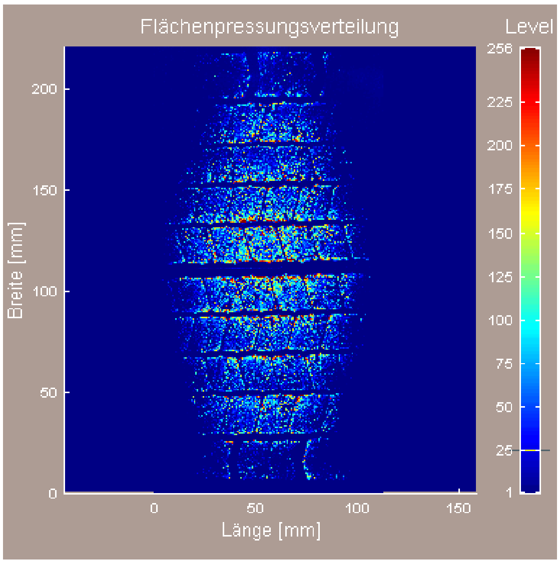


Figure 4.36 - 495/45R22.5, 57.5 kN, 9.5 bar

Table 4.18 - Parameters of the static footprints

Figure	Tyre size	'Pressed area' [1] (mm^2)	Tyre load (kN)	Tyre pressure (bar)
4.30	295/60 R22.5 left	16900	28.75	9.5
4.31	295/60 R22.5 right	13392	28.75	9.5
4.32	315/80 R22.5 left	13916	28.75	7.5
4.33	315/80 R22.5 right	12284	28.75	7.5
4.34	385/65 R22.5	20740	45	9.5
4.35	385/65 R22.5	29416	57.5	9.5
4.36	495/45 R22.5	23036	57.5	9.5

[1] Pressed area is defined as the tyre area which is in contact with a road surface. Gaps in the road surface are not included in the pressed area nor are the grooves of the tyre profile.

The following conclusions can be drawn from the footprints.

1) The 295/60R22.5 twin tyres (Figure 4.30 and 4.31) with a smaller diameter than the 315/80R22.5 twin tyres (Figure 4.32 and 4.33) show shorter footprints and more areas of higher surface pressure under the same tyre load, but with higher tyre pressure of the tyres with smaller diameter.

2) The surface pressure distribution of the 315/80R22.5 twin tyres (Figure 4.32 and 4.33) is similar to that of the 495/45R22.5 super single tyre Figure 4.36 although the 495 tyre has a higher inflation pressure.

3) Under the same tyre load, the 385/65R22.5 (Figure 4.35) single tyre shows more areas of higher surface pressure than the 315/80R22.5 twin tyres (Figure 4.32 and 4.33).

4) The different tyre loads in Figure 4.34 and 4.35 can be seen clearly. The 385/65R22.5 tyre shows a slight longitudinal enlargement of the footprint surface with higher tyre load (Figure 4.35) compared to Figure 4.34, but also more areas of higher surface pressure.

4.5 RELATIVE EFFECT OF TYRES ON PAVEMENT PERFORMANCE UNDER CONTROLLED CONDITIONS

4.5.1 Introduction

Section 4.5 attempts to answer the research questions 3) to 6), as formulated in section 4.3.9. These relate to the relative effect of tyres on pavement performance under controlled conditions (tyre inflated as recommended, dual tyres equally loaded).

1) What is the relative effect of wide base singles and dual assemblies for equal inflation pressures (or equal size of contact areas) and equal loads.
2) What is the relative effect of tyre inflation pressure of the current tyres or size of contact area at equal load for wide base singles and dual assemblies.
3) What is the effect on pavement wear of possible future lower or higher tyre inflation pressures at equal load for wide base singles and dual assemblies.
4) What is the relative effect of tyre diameter (or the shape of the contact area) for wide base singles and dual assemblies for equal inflation pressures (or equal size of contact areas) and equal loads.

It should be stressed that in all these questions, tyres are to be compared at equal axle loads. This is to separate the effects of tyre parameters (such as footprint width, diameter, inflation pressure, etc.) from effects of load magnitude.

Searching for the answers to these questions, literature surveys were first made into available experimental data on the relative pavement wear effects of tyre type/size at different inflation pressures and wheel loads. These surveys are reported in sections 4.5.2 and 4.5.3. Then, additional research was executed within the framework of TG3, including experimental tests of pavement response and performance under several tyre types. These experiments are discussed in sections 4.5.4 to 4.5.7. Numerical simulations were also executed, reported in section 4.5.8 and 4.5.9. The data from all these sources were combined into a table of relative pavement wear effects. This was used for input in regression analysis, aiming to quantify the individual contributions of tyre type (single / wide base / dual), inflation pressure (or differences from the optimum pressure for a given load), footprint width and tyre diameter, as specified in the definition of the tyre configuration factor TCF in section 4.3.8.3. This is reported in section 4.5.10.

4.5.2 Results from literature: effects of tyre type/size and inflation pressure

A literature survey was executed into experimental studies, providing response and/or performance data of pavements, when loaded with different types of tyres (Groenendijk 1999). The study aimed to provide an inventory of the ‘state of the art’ knowledge regarding relative pavement wear ratios of wide base single and dual truck tyres.

Of interest is the behaviour on thin, medium and thick flexible pavements (asphaltic layer thickness of 100, 200 and 300 mm respectively). If possible, the relative pavement wear effects should include the effect of lateral wander.

Main attention was focussed on experimental work, mostly limited to the last decade. This means that older work (mainly concerning obsolete tyres) and modelling studies without experimental validation were neglected.

An extensive identification of relevant literature was already executed, resulting in the COST 334 literature database (Molzer 1998). Therefore the scope of this literature survey was restricted to the literature already identified in that database. It should be noted, however, that this database, although certainly the most comprehensive in its field, does not contain many references reporting experimentally determined data on (relative) pavement wear effects of different wheel load configurations, or even on (relative) pavement responses. Furthermore, multiple articles by the same author often referenced the same experimental work. So it must be concluded that relatively little experimental work has been done in this area. Helpful and comprehensive reviews are those by Evensen et al. (1992), Senstad et al. (1992) and McLean et al. (1995).

The data summaries from the literature review are presented in Annex I, presenting the original test results from the source. These are separated into data about actually measured pavement performance and data about measured responses and modelled performance. The data are grouped by test, sometimes combining information from different sources describing the same test. After the completion of the literature review (Groenendijk 1999), two previously unknown pieces of research (Gramsammer 1997, Nunn 2000) were identified by TG3, the results of which are also incorporated in Annex I in a similar format as the previously identified research.

The study aimed to present the results from literature in the format of ‘relative pavement wear ratios’, the ratio of the wear caused by a specific tyre under certain conditions (primarily wheel load) and the wear caused by a reference tyre under the same conditions. As stated and explained in section 4.3.8.2, TG 3 chose to express this ‘relative pavement wear ratio’ (PWR) as a ‘Life Ratio’ (PWR_L) for fatigue cracking and secondary rutting, and a ‘Distress Ratio’ (PWR_D) for primary rutting. When the literature survey was executed, primary and secondary rutting were not separated as strictly as they were later on, although the difference was well noted.

Unfortunately, some researchers did not specify the tested tyres, e.g. Corté (1994) and Addis (1992), so these results could not be used. Table 4.19 shows the tyre/pavement/distress combinations for which PWR data were found. (Note that differences in wheel load and/or tyre pressure do exist between the different tests, and that the PWR for rutting concern different distress modes as indicated below the table.) These PWR values are incorporated in the database for regression analysis, discussed in section 4.5.10.

Table 4.19 - Inventory of available Pavement Wear Ratio information

Tyre size	Fitment	Thin pavement (100 mm AC)		Medium pavement (200 mm AC)		Thick pavement (300 mm AC)	
		cracking	rutting	cracking	rutting	cracking	rutting
385/65R22.5	wide single	Hu, Kr	Kr[6]	Hu, Se		Se	**As[3], Nu[3]**
315/80R22.5	dual						
295/60R22.5	dual						
295/80R22.5	dual						
315/70R22.5	dual						
10R22.5	dual						**Gr[3], Ha[4]**
11R22.5	dual	**Bo**	Ak[1], **Bo[2]**, Sh[7]	**Bo,** Se	Ak[1], **Bo[2]**	Se	
12R22.5	dual	Hu, Kr	Kr[6]	Hu			
425/65R22.5	wide single	**Bo**	Ak[1], **Bo[2]**	**Bo,** Ma, Se	Ak[1], **Bo[2]**	Se	
495/45R22.5	wide single						**Gr[3], Ha[4]**
245/75R22.5	dual			Se		Se	
265/70R19.5	dual	Hu		Hu			
10R20	dual		**Pi[5]**				
11R20	dual						**Nu[3]**
12R20	dual			Ma			**As[3]**
350/70R19.5	wide single	Hu		Hu			
14/80R20	wide single		**Pi[5]**				
15R22.5	wide single		Sh[7]				
16.5R22.5	wide single		Sh[7]				
445/65R22.5	wide single	Hu, Kr	Kr[6]	Hu			
18R22.5	wide single		Sh[7]				

Bold references indicate actually measured performance

Ak = Akram et al.(1993), McLean et al. (1996)
As = Gramsammer et al. (1997)
Bo = Bonaquist (1992, 1993), Bonaquist et al. (1989), McLean et al. (1996)
Gr = Gramsammer et al. (1998), Penant (1998)
Ha = Halliday et al. (1997), Penant (1998)
Hu = Huhtala et al.(1989, 1990, 1992), Evensen et al. (1992), McLean et al. (1996)
Kr = Krarup (1992, 1994a, 1994b, 1995),
Ma = Mante et al. (1995b), Groenendijk et al.(1997b), Groenendijk (1998)
Nu = Nunn (2000)
Pi = Pidwerbesky (1995), Pidwerbesky et al. (1990)
Se = Sebaaly (1992), Sebaaly et al.(1992), McLean et al. (1996)
Sh = Sharp et al. (1986), McLean et al. (1996)

[1] predicted deformation in the subgrade
[2] measured rutting, 30-50% originating in bituminous layers, 50-70% originating in base
[3] measured rutting, 100% originating in bituminous layers, (PWR_D value)
[4] measured rutting, origin unspecified
[5] measured rutting, mainly originating in base (PWR_D value)
[6] predicted deformation in granular base, subbase and subgrade
[7] predicted unspecified distress, probably mainly deformation in granular layers

4.5.3 Results from literature: effects of tyre diameter

A separate literature review (Penant 2000a) was executed, aiming to provide an inventory of the state of the art knowledge regarding the different pavement damages caused by different diameter tyres. Searching in the COST 334 TG1 literature database, only few elements were found about the effect of a tyre smaller diameter on pavement damage.

Huhtala et al. (1989) relate response measurements made at Virttaa test fields, for two pavements with an asphaltic thickness of 80 and 150 mm. A comparison was made between twin 12R22.5 and 265/70R19.5, for several axle loads and tyre inflation pressures. The difference in diameter is 20%. It was found that smaller twin tires are more aggressive than normal size twin tires by a factor of 1.5 to 2.0. However, it is quoted that tire pressures differed, based on recommended inflation pressures and a variation of 20% more and less, but the values are not quoted. The smaller tyres have probably a higher inflation pressure and the result derives both from the tyre size and inflation pressure level.

Sebaaly et al. (1992) relate pavement response measurements published in 1992 on two flexible pavements, thin and thick. Pavement wear ratios (PWR) were determined for fatigue cracking and rutting. The PWR for rutting were based on measured surface deflections (and calculated stresses in the subgrade), which means they include the deformation in all layers.

Among the different tested tires were 11R22.5 inflated at 120 psi and 245/75R22.5 at the same pressure. They were tested on single and tandem axles with different axle loads. The tyre diameters are not quoted. The difference must be about 12%. The main results are shown in Table 20.

Table 4.20 – Tyre configuration factors for 11R22.5 and 245/75R22.5 (Sebaaly et al. 1992)

Section	Tyre	Pressure (psi)	Axle	Load (lbs/axle)	PWR for 10% fatigue	PWR for 45% fatigue	PWR for rutting
Thin	11R22.5	120	Single	17600	1.0	1.0	1.0
Thin	245/75R22.5	120	Single	17600	1.0	1.0	1.1
Thin	11R22.5	120	Tandem	17200	0.8	0.8	1.5
Thin	245/75R22.5	120	Tandem	17200	1.0	1.0	1.6
Thick	11R22.5	120	Single	17600	1.0	1.0	1.0
Thick	245/75R22.5	120	Single	17600	1.3	1.3	1.3
Thick	11R22.5	120	Tandem	17200	0.8	0.8	1.4
Thick	245/75R22.5	120	Tandem	17200	0.9	0.9	1.5

Sebaaly et al. (1992) state in conclusion, "smaller-size dual tires had slightly higher strains and deflections than conventional duals…". These results were also described in Sebaaly (1992) but they were not discussed there.

Ford et al. (1990) describes the main truck tyre design factors and relates different results extracted from the literature. He quotes contact pressure results between 11R24.5 duals at 105 psi and "downsized" 215/75R17.5 duals at 135 psi. The diameter difference is about 30%. The contact pressure is higher for the downsized and higher inflated duals (23% for the maximum value and 57% for the average). There is no analysis of either inflation pressure effect in this case or description of pavement induced damage.

Conclusion.

Literature state of the art knowledge is rather limited about the influence of tyre diameter on pavement damage. There are just some pavement response measurements, which often cumulate the effects of the tyre diameter and of the inflation pressure. They go in the sense of a slightly higher pavement damage with smaller diameter tyres. These results were not validated by full scale rutting or fatigue experiments.

4.5.4 Results from British pavement response and performance tests

4.5.4.1 Introduction

Within the framework of COST 334, full scale pavement response and performance tests were carried out using TRL's Pavement Testing Facility (see Figure 4.37), as part of the British contribution to COST 334 (Blackman et al. 2000). Two pavement structures were tested, one comprising an asphalt thickness of 100 mm, the other with an asphalt thickness of 200 mm. Subgrade strains were measured under six different tyre configurations at several wheel loads and inflation pressures. The development of rut depth was measured under two wheel load configurations, both wide single tyres. Pavement temperature was maintained at 20° and 30°C, by means of infrared heaters.

Figure 4.37 – TRL Pavement Testing Facility

4.5.4.2 Test pavements and instrumentation

Both pavements were constructed in the concrete test pit of the Pavement Testing Facility, on top of a 225 mm crushed limestone subbase, lying on an imported London clay subgrade of about 3-4% CBR. The thin pavement comprised a 100 mm roadbase layer of Heavy Duty Macadam (HDM) of 28 mm nominal aggregate size. The 200 mm pavement comprised an identical 100 mm HDM roadbase layer, topped by a 50 mm thick binder course of Dense Bitumen Macadam (DBM) of 20 mm nominal size, and a 50 mm Hot Rolled Asphalt (HRA) surface course of 14 mm aggregate. Due to stepped surface levels of subgrade and subbase, the surfaces of both pavements were at the same level. The asphaltic layers were laid perpendicular to the driving direction of the test wheels.

Each pavement was divided into three sections of 1.80 m wide. Each of these was instrumented along the centre line with three vertical LVDT strain gauges in the subgrade layer, with their centres 150 mm below the subgrade surface (475 and 575 mm below the pavement surface, for the 100 and 200 mm pavement respectively), and horizontal distances of 0.75 m. The test pavement layout is shown in Figure 4.38.

FWD measurements on the sub-base and the finished pavement of all sections, together with strain measurements under a moving wheel load, showed that section 2 had slightly higher stiffness than the other sections. Therefore, sections 1 and 3 were chosen for comparative measurements of rutting performance. Section 2 of both test pavements was used for the response measurements, comparing the different load configurations.

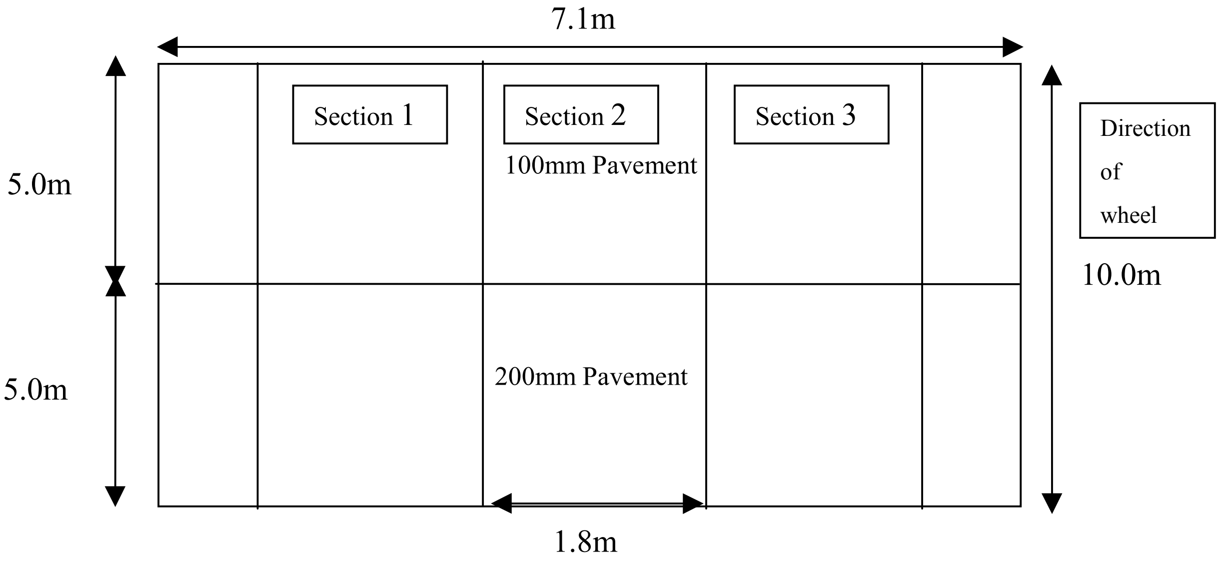


Figure 4.38 – Test pavement layout

4.5.4.3 Response measurements

For the response measurements, the pavements were loaded at 20°C pavement temperature by the six following tyres:

- 295/60R22.5 dual,
- 295/80R22.5 dual,
- 315/70R22.5 dual,
- 315/80R22.5 dual,
- 385/65R22.5 wide-base single,
- 495/40R22.5 wide-base single.

The wheel loads were 30, 44 and 56.5 kN. The inflation pressure was varied between 5 and 10 bar, also incorporating some sets of unequal inflation pressure for the dual tyres.

Subgrade strains were measured with the centre of the wheel configuration at several transversal positions, ranging between ±450 mm on either side of the centre line, in 50 mm increments. The measured maximum subgrade strains are pictured in Figure 4.39 and Figure 4.40. The values under a 44 kN wheel load are tabulated in Table 4.21 and Table 4.22. (NB. The figures are based on one gauge per section, whereas the tables are based on the average of three gauges per section.) These values include a correction for the influences of strain ‘development’ during repeated loading, and strain ‘recovery’ during periods without loading. From Table 4.21 and Table 4.22, strain ratios were calculated per section, relative to the 315/80R22.5 tyre at 8 bar. These values were converted to Life

Ratios per section, using a fourth power relationship. The average values over all sections per pavement thickness are shown in Table 4.23.

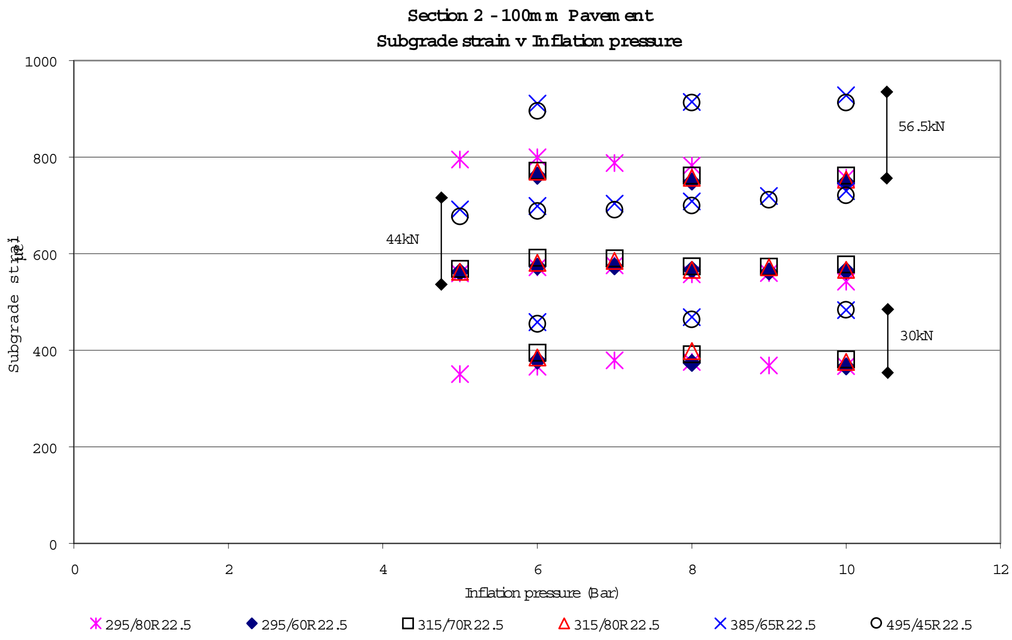


Figure 4.39 – Subgrade strain in the 100 mm pavement as a function of tyre type, wheel load and inflation pressure

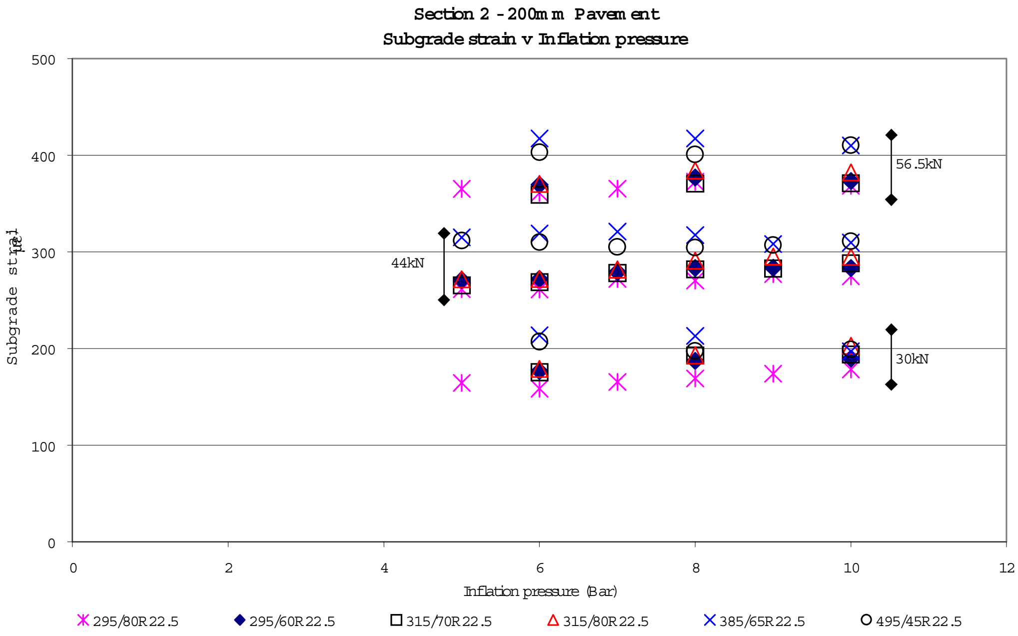


Figure 4.40 Subgrade strain in the 200 mm pavement as a function of tyre type, wheel load and inflation pressure

Table 4.21 – Maximum subgrade strains (µm/m) in 100 mm asphalt pavement at 475 mm depth

	Section 1			Section 2			Section 3		
	Inflation pressure (bar)			Inflation pressure (bar)			Inflation pressure (bar)		
Tyre size	10	8	6	10	8	6	10	8	6
315/80R22.5	997	955	957	644	650	633	792	786	764
295/60R22.5	985	988	973	643	649	644	764	765	754
295/80R22.5	1027	1045	1026	637	653	642	800	794	778
315/70R22.5	935	939	933	646	654	642	774	776	753
385/65R22.5	1195	1197	1170	808	790	792	967	966	967
495/45R22.5	1208	1172	1174	810	778	776	937	907	920

Table 4.22 – Maximum subgrade strains (µm/m) in 200 mm asphalt pavement at 575 mm depth

	Section 1			Section 2			Section 3		
	Inflation pressure (bar)			Inflation pressure (bar)			Inflation pressure (bar)		
Tyre size	10	8	6	10	8	6	10	8	6
315/80R22.5	313	312	312	282	278	270	283	280	280
295/60R22.5	332	332	323	277	275	272	280	273	272
295/80R22.5	309	311	303	278	278	269	297	290	289
315/70R22.5	311	312	303	281	277	270	284	280	274
385/65R22.5	345	348	357	305	305	310	325	326	329
495/45R22.5	370	354	362	303	295	299	322	311	315

Table 4.23 – Distress ratios in 100 and 200 mm asphalt pavement, averaged over all sections per pavement thickness

	100 mm asphalt thickness			200 mm asphalt thickness		
	Inflation pressure (bar)			Inflation pressure (bar)		
Tyre size	10	8	6	10	8	6
315/80R22.5	1.06	1.00	0.93	1.04	1.00	0.96
295/60R22.5	0.93	0.95	0.91	0.99	0.93	0.90
295/80R22.5	1.00	1.03	0.96	1.13	1.08	1.01
315/70R22.5	0.94	0.97	0.90	1.03	1.00	0.90
385/65R22.5	2.38	2.31	2.25	1.59	1.61	1.72
495/45R22.5	2.33	2.03	2.06	1.71	1.48	1.58

4.5.4.4 Performance measurements

For the performance measurements, section 1 was trafficked by a 385/65R22.5 at 4.5 tonne and 10 bar, and section 3 was trafficked by a 495/45R22.5 at 4.5 tonne and 8 bar. Loading was bi-directional and lateral wander was applied, according to a Laplace distribution of the wheel centre positions, with a lambda value of 0.12 m (corresponding with a standard deviation of 0.17 m), as found by Blab (1995) for lane widths around 3.50 m and traffic speeds around 60-80 km/h.

After 57399 load passes at a pavement temperature of 20°C, the thin pavements in both sections 1 and 3 were deemed to have failed based on rut depths over 14 mm, subgrade strains greater than 6000 µm/m and severe alligator cracking in the asphalt layer. The asphalt of the thin pavements was then replaced by reinforced concrete to enable continuation of the trafficking of the thick sections.

After 111549 passes of both tyre types, the pavement temperature was increased to 30°C, because of the slow development of rutting in the thick pavement. The test was stopped after 310099 load passes. At that moment, the rate of rutting was rather slow and there were no visible signs of cracking or pavement deterioration.

Rut development was measured in two ways, both with a 2 m straightedge and wedge, and with optical levelling. Figure 4.41 shows the development of the rut depth, measured with straightedge and wedge. Figure 4.42 shows the ratio of the rut depth under both tyres.

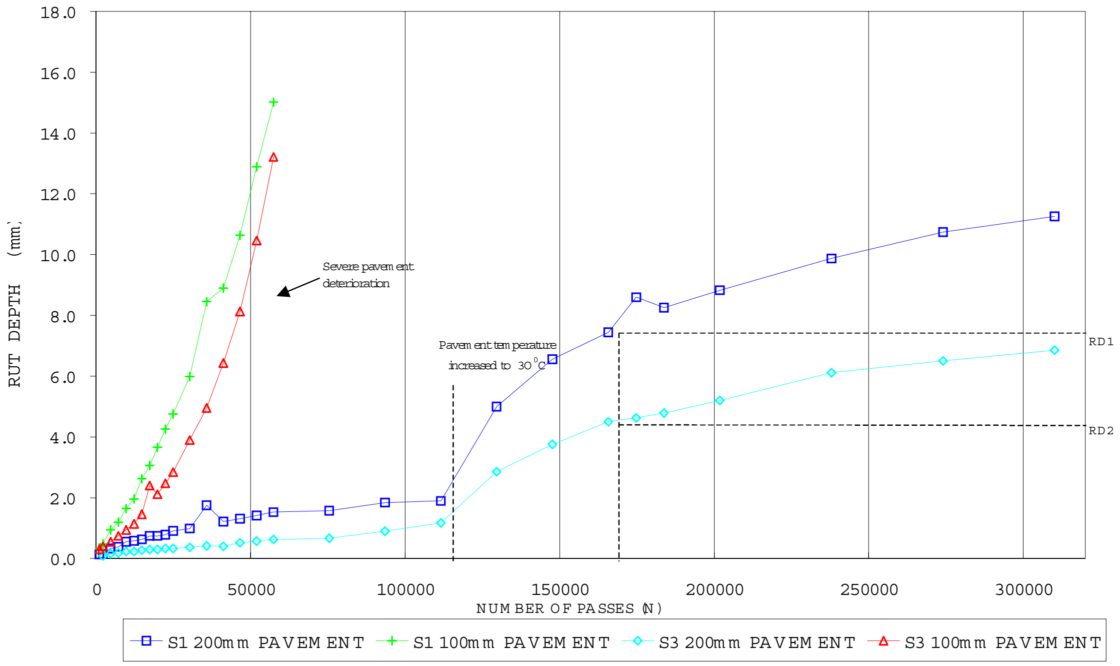


Figure 4.41 – Rut depth development with loading, section 1 loaded by 385/65R22.5 at 4.5 t and 10 bar, section 3 loaded by 495/45R22.5 at 4.5 t and 8 bar.

Figure 4.42 – Ratio of rut depth 385/65R22.5 over rut depth 495/45R22.5

From Figure 4.42 was concluded that the Distress Ratio of the 385/65R22.5, relative to the 495/45R22.5 was 1.7 for the 200 mm pavement and 1.5 for the 100 mm pavement.

4.5.5 Results from Dutch pavement performance tests

4.5.5.1 Introduction

Within the framework of COST 334, full scale accelerated pavement tests were carried out using the Lintrack heavy traffic simulator (see Figure 4.43), as part of the Dutch contribution to COST 334 (Houben et al. 1999a, 1999b). The development of rut depth was measured of two test pavement structures, subjected to four different wheel load configurations. Pavement temperature was maintained at about 40°C surface temperature (±1-2°C), by means of infrared heaters.

Figure 4.43 – Lintrack accelerated pavement testing facility

4.5.5.2 Test pavements

The pavement structures consisted of:

- 40 mm Dense Asphalt Concrete (DAC) wearing course
- 60 mm Open Asphalt Concrete (OAC) binder course
- 80 mm Stone Asphalt Concrete (STAC) base course
- 90 mm Stone Asphalt Concrete (STAC) base course
- 250 mm Cement bound Asphalt GRAnulate (AGRAC) base
- 5m Eastern Scheldt sand subbase / imported subgrade
- clay / peat natural subgrade

After the tests on the first structure, the two top layers were changed (with the same mix design, but a harder bitumen), creating the second structure. The base and the two STAC layers served in both test pavements. This means these bottom layers already were subjected to 34,000 load repetitions in the first test, prior to testing of the second structure.

The AGRAC base material consists of 85% (by mass) asphalt granulate 0/40 mm and 15% river sand. To fulfil the strength requirement (compressive strength at least 2.0 MPa after 7 days) 3.5% cement and 6% water are added.

The STAC 0/22 mm (size of granular aggregate) material consists of 50% (by mass) asphalt granulate 0/40 mm and of 50% virgin aggregates of crushed stone (granite) composed of gradings 8/16 and 16/22 mm, crushed sand and filler. The penetration of the added bitumen is 80/100.

The OAC 0/22 mm material also consists of 50% (by mass) asphalt granulate and furthermore of 50% virgin aggregates of crushed stone (granite) composed of gradings 4/8, 8/16 and 16/22 mm, crushed sand and filler. The penetration of the added bitumen is 80/100.

The DAC 0/16 mm material only contains virgin aggregates: crushed stone (granite) composed of the gradings 2/6, 4/8, 8/11 and 11/16 mm, sand (75% crushed sand and 25% river sand) and filler. 80/100 pen bitumen was used in the first test pavement (according to the 1990 Dutch standard specifications), 45/60 pen bitumen was used in the second pavement (according to the 1995 Dutch specifications).

Acceptance testing showed that:

- individual layer thicknesses on both pavements showed some variation, but the overall thickness was as specified;
- the OAC in the first pavement had rather low void content and may therefore be more rut susceptible;
- the OAC and DAC of the second pavement had rather low bitumen content and penetration value, and may therefore be more rut resistant;
- bonding between layers was locally somewhat poor in the first pavement, whereas a good bond was achieved in the second pavement.

To enable the testing of the pavement structure in 4 separate wheel tracks, the total width of the test pavement was taken as 15.0 m. For practical reasons this was subdivided in 2 times 7.5 m (see Figure 4.44). The distance between 2 adjacent wheel tracks is 3.5 m and the distance of a wheel track to the pavement edge is 2.0 m.

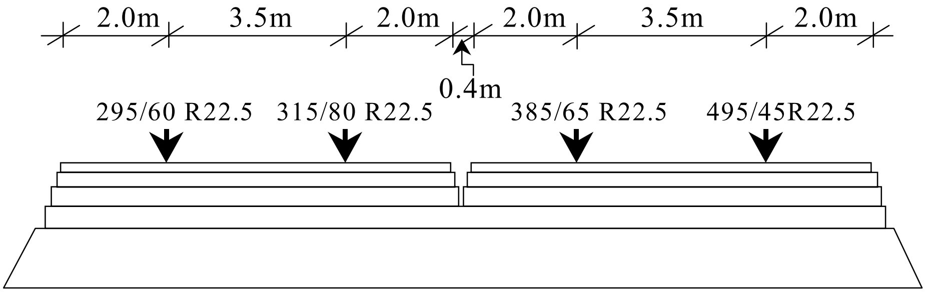


Figure 4.44 - Schematic cross section of the test pavement (not on scale) and tyre types in the rutting performance test (Houben et al. 1999a, 1999b)

4.5.5.3 Loading

Four wheel load configurations were tested on both test pavements, each having its own wheel track (see Figure 4.44). The load characteristics are listed in Table 4.24. The tested tyres are shown in

Table 4.24 – Load characteristics

Description	Design diameter (mm)	Tyre size designation	Load (kN)	tyre pressure before loading	Estimated tyre pressure during loading
Low diameter alternative dual tyre for drive axle	926	295/60R22.5	57.5	0.9 MPa	0.94 MPa
Standard dual tyre for drive axle	1076	315/80R22.5	57.5	0.7 MPa	0.74 MPa
Standard wide single tyre for trailer axle	1072	385/65R22.5	45.0	0.9 MPa	0.94 MPa
Extra wide single tyre for drive axle (prototype)	1018	495/45R22.5	57.5	0.9 MPa	0.94 MPa

Figure 4.45 - Tyres tested in NL pavement performance test, left to right: 315/80R22.5 dual, 295/65R22.5 dual, prototype 495/45R22.5, 385/65R22.5

On the first test pavement, each wheel track first was subjected to 1000 load repetitions of the 385/65 R 22.5 tyre, with a 45 kN wheel load and 0.9 MPa tyre pressure. This was done to check whether the tracks were sufficiently comparable. After these initial 1000 load repetitions, each wheel track was loaded by 33,000 load repetitions of its own tyre type. Every wheel track thus was subjected to a total of 34,000 load repetitions.

On the second pavement, the same initial loading as above was applied on all tracks. After that, each track was loaded by 36,000 load repetitions of its own tyre type, making a total of 37,000 load repetitions per track.

Lateral wander was applied, using a Laplace distribution of the wheel centre position, with a lambda value of 0.12 m. For practical limitations, this distribution was truncated at a maximum distance to the wheel track centre of 0.3 m. Because of the limitations in the equipment (the maximum sideways displacement between two subsequent load repetitions is limited to about 0.05 m), it requires a considerable number of load repetitions (some 10,000 to 15,000) before a nearly symmetrical lateral wander distribution is obtained. The non-symmetrical distribution in the early phase of testing will reflect in a non-symmetrical rutting profile. The lateral distribution is exactly the same for every wheel track for the whole range of load repetitions.

4.5.5.4 Measurements

During the performance tests, the transverse profile of the pavement was periodically measured at 7 positions along each track, using a custom profilograph. More measurements were executed, but these are not reported here. From the measured rutting profiles the development of the following parameters was analysed (among others):

- the maximum rut depth under each tyre of a dual tyre system or below a super-single tyre, relative to the original pavement surface;
- the height of the heave at each side of the rut, relative to the original pavement surface;
- the height of the heave between two tyres of a dual tyre system, relative to the original pavement surface;
- the practical rut depth, defined as the maximum height difference between the rutting profile and a straightedge, laid over the rutting profile.

4.5.5.5 Comparison of the four wheel tracks

Comparison on first pavement:

- The overall stiffness behaviour of the structure was very well comparable, based on FWD measurements (50 kN load) prior to loading;
- The rutting behaviour was reasonably well comparable. The wheel track 385/65 showed somewhat less initial rutting (average rut depth, excluding heaves, 2.2 mm after 1000 load repetitions of the 385/65R22.5 tyre) than the other three, comparable, wheel tracks (average rut depth, excluding heaves, 3.1 to 3.9 mm after 1000 load repetitions of the 385/65R22.5). However, the difference in initial rut depth could be due (mainly) to the fact that the temperature of the 385/65 track during initial loading (34°C) was somewhat lower than at the other tracks (38°C).

Comparison on second pavement:

- The overall stiffness behaviour of the structure was very well comparable, based on FWD measurements (50 kN load) prior to loading;
- The rutting behaviour was reasonably well comparable. The wheel track 315/80 showed somewhat less rutting than the other wheel tracks, for which no explanation was found.

4.5.5.6 Rutting performance results

To enable a fair comparison between the rutting caused by each type of tyre, the pavement surface level after the initial 1000 load repetitions was taken as the reference (zero) level for the rutting performance test. This means that the development of rutting parameters, as a function of the number of load repetitions, starts at zero, although the wheel tracks actually had an initial rut.

Figure 4.46 shows the development of the practical rut depth on the two test pavements. Table 4.25 shows the practical rut depths at the end of the tests. In the first pavement 80/100 pen bitumen was applied in the Dense Asphalt Concrete wearing course and the four wheel tracks of this pavement were subjected to 33,000 load repetitions. In the second test pavement 45/60 pen bitumen was used for the wearing course and the four wheel tracks were subjected to 36,000 load repetitions. The figure clearly shows that the development of rutting is not only dependent on the type of tyre (with its specified load and tyre pressure) but also on the asphalt pavement structure and the materials used (or the pavement temperature).

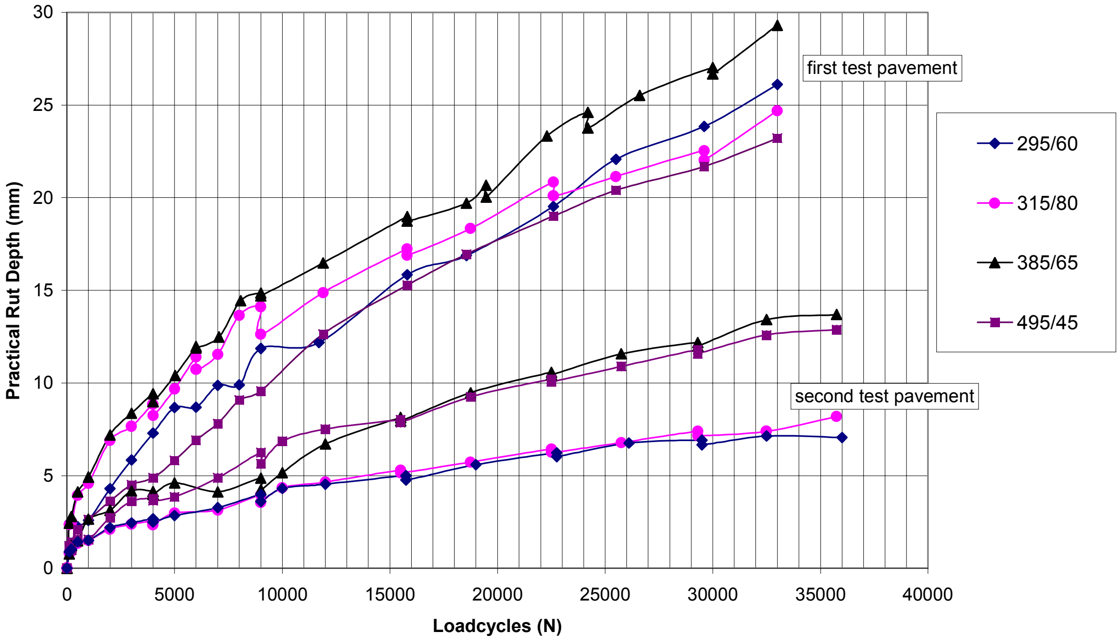


Figure 4.46 – Development of 'practical rut depth' on the two tested pavements (based on Houben et al. 1999a and 1999b)

From the measurement results, the following conclusions were drawn regarding the differences between the four tested tyres.

First test pavement:

- The prototype extra wide single tyre 495/45 R 22.5 showed the best behaviour, which means that the rutting was smallest, while the rutting process remained stable.
- On the contrast the standard wide single tyre 385/65 R22.5 showed the worst behaviour, which means that the rutting was greatest while the rutting process became unstable after about 20,000 load repetitions.
- The standard dual tyre 315/80 R22.5 showed a similar behaviour as the prototype extra wide single tyre 495/45 R22.5 although the rutting was somewhat greater.
- The alternative low diameter dual tyre 295/60 R22.5 showed the same rutting behaviour as the prototype extra wide single tyre 495/45 R22.5 up to about 20,000 load repetitions, but after that an unstable rutting process occurred.

Second test pavement:

- At long term (i.e. for the relevant practical rut depths) the prototype extra wide single tyre 495/45 R 22.5 caused less rutting than the standard wide single tyre 385/65R22.5
- The standard dual tyre 315/80R22.5 exhibited a remarkable good rutting behaviour (i.e. small practical rut depths) compared to both wide single tyres. A provisional explanation for this good behaviour is that through the combination of the great overall width of a dual tyre system and the stiff wearing course the stress levels in the Stone Asphalt Concrete layers are smaller than in the case of a wide single tyre, and by consequence the permanent deformation in the Stone Asphalt Concrete layers caused by the standard dual tyre is much smaller than that caused by single tyres. This provisional explanation is confirmed by the results of the performed layer thickness

> measurements but needs further research to be verified. However, this explanations does not explain the differences in relative ranking between the first and second test pavement. Therefore, the good behaviour of the 315/80R22.5 on the second test pavement may also be due to a better rut resistance of its track, relative to the other tyre tracks.

Distress ratios can be calculated from the practical rut depths in Table 4.25. However, a load correction has to be applied to the 385/65 data, as this tyre was tested at 45 kN wheel load, and the other tyres at 57.5 kN. This can be done using the following formula:

> Distress ratio tyre A = (rut depth tyre ‘A’ / rut depth reference tyre) * (load reference tyre / load tyre ‘A’)^n

Generally, a fourth power load dependency for pavement distress is used, meaning that n=4 in the formula above. However, TG3 considered this value too high for the primary rutting distress mode. Based on experience, a ‘power value’ for load dependency of one to two was considered more likely. Therefore, corrected distress ratios were calculated using both n=1 and n=2.

Figure 4.46 shows that the ranking of the tested tyres is not the same for both test pavements. This is also clear from the Distress Ratios in Table 4.25. This unequal ranking could be caused by differences between the different tracks, although they were considered to be comparable. Therefore, Distress Ratios were calculated, corrected for initial rutting speed, using the following formula:

> (Corrected) distress ratio tyre ‘A’ = (rut depth tyre ‘A’ / rut depth reference tyre) * (initial rut depth at reference tyre track / initial rut depth at track tyre ‘A’) * (load reference tyre / load tyre ‘A’)^n.

All these corrected distress ratios are shown in Table 4.25.

Table 4.25 – Distress ratios for the two tested pavements

Test pave-met	Tyre size	Load (kN)	Initial pract. rut depth after 1 kc (mm)	Pract. rut depth after 33 or 36 kc (mm)	Pavement Wear Ratio PWR_D (n=1)	Pavement Wear Ratio PWR_D (n=2)	PWR_D (n=1) corrected for initial rutting	PWR_D (n=2) corrected for initial rutting
1	315/80R22.5	57.5	5.46	24.7	1	1	1	1
1	295/60R22.5	57.5	4.88	26.11	1.06	1.06	1.18	1.18
1	495/45R22.5	57.5	3.88	23.21	0.94	0.94	1.32	1.32
1	385/65R22.5	45	-[1]	29.3	1.52	1.94	-[1]	-[1]
2	315/80R22.5	57.5	2.95	8.2	1	1	1	1
2	295/60R22.5	57.5	2.16	7.06	0.86	0.86	1.18	1.18
2	495/45R22.5	57.5	3.46	12.88	1.57	1.57	1.34	1.34
2	385/65R22.5	45	3.53	13.7	2.13	2.73	1.78	2.28

[1] initial rut depth at 385/65 track of first pavement was not well comparable due to temperature differences with other tracks.

4.5.5.7 Conclusions

Table 4.25 shows that the correction of the PWR_D values for initial rutting resolves the differences in the ranking of the tyres on both test pavements.Therefore, TG3 chose to use these corrected values. TG3 also chose for correction of load differences using a power value of n=2, as this was estimated to be the most realistic value. So the values in the last column of Table 4.25 were used for further analysis.

4.5.6 Results from French pavement response tests

4.5.6.1 Introduction

An experiment was carried out on the LCPC Manège de Fatigue in collaboration with Michelin (who supplied the tyres, wheels assemblies and relative data) as part of the French contribution to COST 334 (Odéon et al. 2000). Its goal was to compare the effects on pavement durability (considering the longitudinal and transverse strains at the bottom of the bound layers as well as the vertical strains at the top of the unbound layers) of different tyre mounts and loading conditions chosen to answer four different questions defined in the research program of COST 334. These questions apply to the influence of:

- Tyre inflation pressure (question 5).
- Tyre external diameter (question 6).
- Unequal load sharing between the two tyres of a dual assembly (question 8).
- Under or over-inflation of tyres (question 9).

The effects on pavement fatigue life were studied from strain measurements and further computational analysis. The analyses of both the experimental results and the computations were made without considering lateral wander.

4.5.6.2 Test pavement

The pavement structure consisted of:

- A 0.08 m thick asphalt concrete course (AC 0/14 with 5,7% of 35/50 Elf-Donges bitumen; Ring & Ball temperature = 50.5°C, 0/2 fraction: 36% crushed sand from Cusset; 2/14: La Noubleau quarry).
- A 0.40 m thick road base asphalt course (RBA 0/14 with 4,6% of 35/50 Elf-Donges bitumen (class 3); La Noubleau quarry).
- A 0.40 m thick course of untreated granular material (UGM 0/20, Maraîchères quarry).
- An about 0.30 m thick coarse 80/150 subbase.
- About 1.5 m micaschist (poor, modulus of about 35 MPa).
- A sandy clay subgrade.

This is a very thick and stiff structure, which does not exist in practice on the European road network and was previously used for surface course rutting tests. It was realised that the thickness and stiffness of this structure would reduce the influence of the parameters studied, relative to more common thinner pavement structures. At the time of testing, however, this structure was the only one available.

4.5.6.3 Loading

The loading was effected using the LCPC *Manège de Fatigue,* shown in Figure 4.47.

Figure 4.47 - Manège de Fatigue

Four distinct tyre mounts were tested, namely a reference dual assembly (315/80R22.5), a low diameter dual assembly (295/60R22.5), a wide single tire (385/65R22.5) and an extra wide single prototype tyre (495/45R22.5). Each tyre mount was attached to an other arm of the manège, with the tyre mount centre at a radius of 19.5 m. For the extra wide single tire and the reference dual assembly, the inflation pressure and/or the applied load were varied. A total of twelve tyre mount configurations were tested, as detailed in Table 4.26.

Table 4.26 – Tested tyre mount configurations

Tyre size	Test n°	Config.	Load (kN)	Pressure (bar)	Diameter (mm)
315/80R22.5	1	Dual	57.5	8.0	1088
	4	Dual	57.5	10.0	
	5	Dual	57.5	6.0 and 10.0	
	6	Dual	57.5	6.0	
	7	Dual	57.5	4.0	
	8	Dual	57.5	11.5	
295/60R22.5	2	Dual	57.5	10.0	929
385/65R22.5	13	Single	45.0	10.0	1069
495/45R22.5	9	Single	57.5	10.0	1010
	10	Single	57.5	8.0	
	11	Single	57.5	11.5	
	12	Single	45.0	10.0	

4.5.6.4 Weather conditions.

The measurements took place between April 13th and 21st 1999.

The ambient temperature varied between 5°C and 18°C; the pavement surface temperature varied between 7°C and 28°C. The temperature at a depth of 50 cm remained fairly constant, at about 14 to 15°C.

In addition hail showers happened during the measurements, causing sudden temperature evolutions at the pavement surface and disturbance to measurement signal acquisition.

4.5.6.5 Measurements

Different sensors were installed in the pavement when built, at a 19.5 m radius:

- Strain gauges located at different depths in the structure:
    - At the bottom of the asphalt concrete course (8 cm depth), in the longitudinal (gauges GL10, GL11 and GL12) and transverse (gauges GT10, GT11 and GT12) directions.
    - At the bottom of the road base asphalt course (48 cm depth) in the longitudinal (gauges GL1 to GL4) and transverse (gauges GT1 to GT4) directions.
    - At the surface of the untreated granular material course (48 cm depth) in the vertical directions (gauges V1 to V3).
- Thermocouples at different depths inside the pavement (number T1 to T5 at, respectively, 48, 33, 18, 8 and 4 cm depth), at the pavement surface (T6) and in the ambient air (T7).

One or two measurement series were made per day. The Manège load module was set on the mean radius of 19.5 m and the measures were carried out for :

- Three lateral positions of the tyre assemblies (centred and shifted by 10.5 cm on each side) in order to determine the maximal strain.
- Two revolution speeds (6.5 and 0.5 rpm, corresponding to about 40-48 and 3-4 km/h, depending on the radius), in order to characterise the pavement behaviour for two different stiffnesses.

Each of the valid 21 strain gauges was thus polled 44 times. To each gauge, an elementary polling consisted in recording the signal during a turn plus a quarter of a turn of the Manège. It was thus possible to see five strain peaks, which corresponded to the passage of four successive arms, with a repetition of the measurement for the first arm for control purpose. For each measurement, the temperature gradient in the pavement was recorded.

The strain amplitude was very weak. The value of most of the longitudinal and transverse strains at the bottom of the road base asphalt course was between about 10 and 20 µm/m and the order of magnitude of the vertical strains at the surface of the untreated granular material course is about 40 to 70 µm/m. In spite of this low strain amplitude, the quality of the recorded signals was good, even when the amplitude was less than 10 µm/m. Indeed there was a low noise level on these signals, the signal/noise ratio being at most of 15%. The peak values significant of the passages of the different tyre configurations were extracted from the raw signals and no filtering was necessary. However, the strain values were not included when less than 2 µm/m.

4.5.6.6 Analysis

The analysis was carried out in four steps :

- A first analysis on the measured peak values, without any processing, leading to a first answer to the questions.
- The adjustment of a model to the measurement results.
- A second analysis using the model and processing the peak values in order to eliminate the influence of temperature variation.
- A tentative extension of the model to other pavement structures.

This analysis dealt only with the structural fatigue behaviour, and not with the surface course rutting behaviour. Therefore, only the measurements at the bottom of the road base

(0.48 m depth) and near the surface of the untreated granular material (about 0.53 m depth) were considered.

Raw measurement results analysis.

The following general remarks can be made:

- The gauges at nominally identical positions gave very similar results (differences 1 to 21% between the minimum and maximum value of three horizontal strain gauges).
- The transverse strains measured at the bottom of the structure were always lower than or equal to the longitudinal strains. This was true whatever the tyre configurations, temperatures and revolution speed of the *Manège*. Nevertheless, the two values are of similar order of magnitude.
- The measured values were always higher at low speed (0.5 rpm, about 3-4 km/h) than at higher speed (6.5 rpm, about 40-48 km/h). In the same way, but to a lesser extent, the measured values were slightly higher at higher air (and pavement) temperature.
- Finally, the vertical strains results show a clear distinction between the tyre mounts loaded at 45 kN from those loaded at 57.5 kN. Indeed, the vertical strain measured at the bottom of the pavement is more sensitive to the global applied weight than to the geometry of application, contrarily to the transverse and longitudinal strains measured at the bottom of the road base bituminous course.

These latter observations confirm common knowledge about temperature and frequency dependent stiffness of bituminous materials, and of the application of St Venant's principle (see 4.3.5.1).

Regarding the four research questions, the raw measurement results did not allow, by themselves, to draw a clear conclusion on the effect of the different studied parameters. This is because the temperature variations in the pavement during the tests modified the behaviour of the structure, making it more or less stiff, and thus affecting directly the results. The analysis had therefore to be pursued in order to erase this temperature effect. This is the main goal of the following modelling phase.

Adjustment of a model to the measurement results

The test pavement was modelled as a linear elastic multilayer structure, using the Alizé program of the LCPC. (A visco-elastic modelling was attempted, but did not achieve a better match with the measured values and relative effects. Therefore the simpler linear elastic model was used.) The bituminous layers were sub-divided into five layers, to enable accounting for varying temperature and load frequency over the pavement thickness.

The material stiffness for the bituminous layer in the model was determined using a Huet-Sayegh model. The material parameters for this model were determined from laboratory testing of the complex stiffness modulus of the materials used. The load frequency (depending on temperature, depth in pavement, and wheel speed) was determined from the measured strain signals.

The tyre configurations were modelled according to their rectangular footprint dimensions (data provided by Michelin) and the pressures exerted on the pavement surface. The rectangular footprint was modelled by the juxtaposition of circular loads.

In the computations, the estimated transverse positions of the gauges (which deviated somewhat from the centre line of the tyre configurations) were taken into account. Also, the physical length of the gauges (0.10 m) was taken into account by averaging the calculated strains over this length. Any possible horizontal rotation of the gauges was neglected, and so were thickness variations of the pavement along the longitudinal profile, i.e. between gauge positions.

Finally, constant adjustment coefficients were applied, dividing all computed horizontal strains (both longitudinal and transversal) in the road base asphalt layer by 1.6, and all computed vertical strains in the unbound granular material by 1.05. This proved necessary to achieve a reasonable match between measured and calculated results.

The results from this adjusted model were compared with the measured results, providing a reasonable match (within 20%). This means that the adjusted model accounted reasonably well for the differences in temperature and wheel speed between the different measurements. Also, the adjusted model gave a good prediction for the relative differences between the different tyre configurations.

Analysis of the results of the adjusted model, at a uniform temperature of 15°C.

Using the adjusted model, the effects of the different tyre configurations were computed at a uniform temperature of 15°C. The results are shown in Table 4.27.

Table 4.27 – Computed strains at 15°C

				0.5 rpm			6.5 rpm		
Tyre configuration	Load (kN)	Pressure (bar)	Lateral position	ε_L (µm/m)	ε_T (µm/m)	ε_V (µm/m)	ε_L (µm/m)	ε_T (µm/m)	ε_V (µm/m)
295/60R22.5	57.5	10.0	centre	-31.1	-26.1	78.0	-21.2	-18.0	56.6
315/80R22.5	57.5	8.0	centre	-28.95	-23.56	76.53	-19.77	-16.27	55.19
	57.5	10.0	centre	-29.13	-23.58	76.73	-19.88	-16.27	55.32
	57.5	6.0 and 10.0	-0.105	-29.2	-24.5	73.4	-19.9	-16.9	53.2
	57.5	6.0 and 10.0	centre	-28.9	-23.6	72.6	-19.8	-16.3	52.8
	57.5	6.0 and 10.0	+0.105	-28.1	-22.1	70.5	-19.2	-15.3	51.4
	57.5	6.0	centre	-28.68	-23.52	76.19	-19.60	-16.23	54.97
	57.5	4.0	centre	-27.92	-23.40	75.25	-19.1	-16.16	54.36
	57.5	12.0	centre	-29.21	-23.59	76.83	-19.94	-16.28	55.39
495/45R22.5	57.5	10.0	centre	-31.37	-29.73	85.72	-21.34	-20.28	61.20
	57.5	8.0	centre	-31.06	-29.70	85.35	-21.14	-20.26	60.95
	57.5	12.0	centre	-31.46	-29.55	85.63	-21.40	-20.16	61.14
	45.0	10.0	centre	-24.67	-23.13	67.06	-16.78	-15.78	47.88
385/65R22.5	45.0	10.0	centre	-24.76	-24.38	68.49	-16.84	-16.59	48.81

At the considered depth (48 cm), the strains have their extreme values under the axis of the single tyres and dual assemblies. Therefore only these results are given.

Regarding the four research questions, the following conclusions could be drawn from the model results.

- Different inflation pressure at the same load level.

  The low diameter 295/60R22.5 dual assembly inflated at 10 bar is more aggressive than the reference 315/80R22.5 dual assembly inflated at 8 bar, for a total load of 57.5 kN. The difference is about 7% (-21.2 vs. -19,77 µm/m) for the longitudinal strains, which are the most detrimental for this pavement. The difference is about 2 to 3% for the vertical strains. This is true at 6.5 rpm as well as at 0.5 rpm. (In this conclusion, the effect of higher inflation pressure is mixed with the effect of smaller tyre diameter. This was realised in the design of this experiment, as the very aim of this question was to compare tyres designed to work at different pressures for the same load. They cannot have the same geometry. TG3 chose to keep the contact area width constant and change the diameter.)

- Different tyre diameter at equal inflation pressure and applied load.

  For the single tires, the 495/45R22.5 (ϕ= 1010 mm) and the 385/65R22.5 (ϕ=1069 mm) were compared, both at 45 kN and 10 bar. The vertical and longitudinal strains are very close (respectively -16,78 and -16,84 µm/m at 6.5 rpm); the difference is about 0,3 %, which is not significant. It can be considered that the two configurations have the same effect on the pavement.

  For dual assemblies, the 295/60R22.5 (ϕ=929 mm) and the 315/80R22.5 (ϕ= 1088 mm) were compared, both at 57.5 kN and 10 bar. The strain difference is slightly higher, in accordance to a larger diameter difference. The 315/80R22.5 generated strains about 6.2 % lower than the 295/60R22.5.

  So when the diameter difference is small (6% - single tyres), this parameter has no effect on pavement life. However, when it is higher (17% - dual tyres) the smaller diameter tyres generate higher strains in the pavement and are more aggressive. (In this conclusion, the effect of diameter differences for the single tyres is mixed with the effect of tyre footprint width differences, as no wide single tyres exist that could avoid this problem. For the dual tyres the footprint widths are almost equal.)

- Imbalanced load sharing between the two tyres of a dual assembly.

  The 315/80R22.5 dual assembly at 57.5 kN and 8 bar was compared to the same assembly at 57.5 kN and 6 and 10 bar. The strain under the dual assembly axis is not much modified by the imbalance: at 6.5 rpm the longitudinal strain changes from -19,77 to -19,8 µm/m, transverse strain from –16.27 to –16.3 µm/m, vertical strain from 55.19 to 55.14 µm/m. However, the extreme values are always found under the tyre which was inflated to 10 bar. Indeed, the computed longitudinal strain is –19.9 µm/m under the 10 bar tyre when it is –19.2 µm/m under the 6 bar tyre. This effect is even more important for the transverse strains (-16.9 and –15.3 µm/m) and vertical strains. It is also more important at low speed. In shifted positions, under the tyre inflated to 10 bar, the strain is the strongest, -19.55 µm/m, while it is -19,49 µm/m under the tyre inflated to 6 bar. It was concluded that on such a thick pavement, the unequal load between the two tyres of the reference dual assembly (315/80R22.5) leads to a slightly increased (about 1%) strain under the most loaded (or inflated) tyre, which "punches" the pavement more.

- Overinflation or underinflation of tyres at the same load.

  The strains under the wide single tyre 495/45R22.5 were compared at 8, 10 and 11.5 bar (all at 57.5 kN). The strains decrease very slightly when the inflation pressure decreases and the tyre footprint lengthens. So, at 6.5 rpm, the longitudinal strain passes from –21.40 µm/m to –21.14 µm/m (-1.2%) when the pressure decreases from 11.5 to 8 bar, for a constant load of 57.5 kN. The order of magnitude is the same at 0.5 rpm. The effect is negligible for the vertical strain. However, the vertical and transverse strains pass by a slight maximum at 10 bar. This is true at 6.5 and 0.5 rpm.

  The reference dual assembly 315/80R22.5 was compared at 4, 6, 8, 10 and 11.5 bar (all at 57.5 kN). At 6.5 rpm, the longitudinal strain passes from –19.94 to –19.10 µm/m (-4.2%) when the pressure decreases from 11.5 to 4 bar, for a constant load of 57.5 kN. The order of magnitude is the same at 0.5 rpm. The effect is less (-1.9%) for the vertical strain. These decreases are rather small when compared to the large inflation pressure decrease (three times).

In conclusion, in the two cases, the longitudinal strain decreases when the inflation pressure decreases, because of the lengthening of the shape of the tyre footprint. However, under the wide base tyre, the vertical and transverse strains are maximal (very slightly) for the intermediate inflation pressure of 10 bar.

It can be observed that the strains computed under the different configurations are very close and the differences are very small. This is due to the extreme stiffness of the tested pavement, which lessens the geometry and pressure influences of the different configurations. However the chosen systematic interpretation method allowed, with a certain confidence, to show the influence of the tyre mount geometry on the pavement strains, according to the tyre footprint and configuration. A weaker structure would have allowed a better discrimination among the tyre mount configuration, which was known from the beginning of the experiment. Therefore, the model was extended to other pavement thicknesses.

Tentative extension of the model to other pavement structures.

The adjusted model was modified to simulate the four pavement structures (see Table 4.6) that were chosen by TG3 as representative for thin, medium and thick pavements in European practice. However, as this involved substantial extrapolation of the model, only qualitative conclusions were drawn.

- A higher inflation pressure (mixed with a lower tyre external diameter) would be more detrimental to the pavements.
- In the case of an important diameter difference (295/60R22.5 vs. 315/80R22.5 dual assemblies), a smaller diameter would be more detrimental to the pavements.
- In the case of unequal load sharing between the tyres of a dual assembly due to inflation pressure differences, the most severe strain, which governs the pavement life, occurs under the most inflated tyre and is close to the one computed under the dual tyre assembly carrying the same load and symmetrically inflated at the same pressure. The pavement life would be similar in these two conditions.
- There is a little positive influence on pavement fatigue of a reduction of tyre inflation pressure. It is less important when the pavement thickness is increased.

Equally loaded and with the same inflation pressure, the ranking of the tyre mounts is qualitatively as follows (increasing aggressivity): reference duals (315/80R22.5), low diameter duals (295/60R22.5), extra wide single tire (495/45R22.5) and wide single tyre (385/65R22.5). However, it was not possible to quantify the actual impact of these differences on the pavement life duration.

4.5.6.7 Conclusions

The experimental pavement used for these comparisons was very thick (0.48 m bituminous material / 0.4 m unbound granular material) and consequently very stiff. The result was that the differences between the configurations were only a few percents. In addition the experiment was made in the open air during several days and the temperature evolutions had an adverse effect on the possibility to draw clear conclusions from the measured values.

The conclusion of the analysis of the raw measured data was that the effects of the studied parameters were minor, in particular when compared to the temperature effects, and the raw measured data could not be analysed in more detail.

However, the measurement quality allowed to attempt a more precise measurement interpretation. This consisted in trying, through the use of a model, to separate the effects of the different studied factors from the other factors, particularly the temperature.

The different configurations were compared this way at a constant temperature (15°C) on the experimental pavement structure. Similar computations were also made for other pavement structures, with different lower stiffness levels.

The main conclusions of this study, valid for the previously described conditions or hypotheses, are the following:

- It is quite possible to separate the effects of the different tyre mounts according to their contact area geometries and to the load they carry. The action on the pavement is less detrimental when the load is spread on a larger total contact area (envelope of the one or two contact areas). Thus, for an equal carried load, a dual tyre assembly is less aggressive than a wide base single tyre. A further full scale experiment would be necessary to quantify this effect on pavement life duration.
- The longitudinal strains (or stresses) measured or computed at the bottom of the structure are always greater than the transverse ones, for all the studied configurations, structures, speeds or temperatures.
- The interpretation of the experimental results, obtained on a very thick pavement, showed a slight influence of parameters such as contact pressure or load imbalance on the structural behaviour of the pavement. In fact, computations carried out on other usual and less rigid pavements showed the same tendencies but are more discriminating. So :
    - The load imbalance caused by an inflation pressure imbalance between the two tyres of a dual assembly is similar to the effect of the same dual assembly carrying the same total load and symmetrically loaded at the highest pressure level.
    - An under-inflated tyre induces less important strains in the pavement and lengthens its life duration. This is due to an increase of the contact area length, with a fairly constant contact area width, when the inflation pressure is reduced.

4.5.7 Results from Finnish pavement response tests

Within the framework of COST 334 TG3, a full scale pavement test was executed by VTT at the Virttaa instrumented pavement test site, as part of the Finnish contribution to COST 334 (Huhtala et al. 2000a). The main goal of the test was to quantify the differences in dynamic loading between different tyre types. This is described more extensively in section 4.7.3. Relevant to this chapter are the measurements of stresses and strains in the pavement structure, when loaded with different tyres at constant (moving) load.

The Virttaa test site of VTT is located about 200 kilometres Northwest from Helsinki on National Highway 41. It is a highway section, widened to 40 m for use as a jet fighter airstrip. The instrumented test pavements are located in the shoulder of the road, so they are loaded only during VTT experiments. For these tests, a section with 150 mm thickness of bituminous layers was used, constructed in 1987. Thicknesses and materials of the test section pavement are shown in Table 4.28. Seven longitudinal strain gauges in line at the bottom of the bituminous layers and three pressure cells at different depths have been used for these measurements.

Table 4.28 - Pavement layers and sensors at the Virttaa test site.

Layer	Thickness [mm]	Material	Depth of sensors [mm]
Asphalt	150	AC80	150
Base	150	Crushed rock	300
Subbase	400	Gravel	500
Subgrade	> 20 m	Sand	800

Figure 4.48- The instrumented test vehicle of the VTT tests

The loading was applied using an instrumented test vehicle, shown in Figure 4.48. The measurements shown here were made under the tractor drive axle at an axle load of 115 kN. The tyres used were a dual 315/70R22.5 XDA at 750 kPa and a wide base single 495/45R22.5 Energy XDA (prototype) at 900 kPa. These tyre pressures follow the manufacturer's recommendation for the applied load. Both tyres were supplied by Michelin. Tests were executed at vehicle speeds of 45 and 80 km/h.

Results on different unbound layer stresses at 80 km/h vehicle speed are presented in Figure 4.49. Similar results were obtained at 45 km/h. The wide base single tyre (495/45R22.5) produces about 21 percent greater stresses in the base layer and about 14 percent greater stresses in the subbase layer, respectively. Subgrade stresses are equal with both tyres.

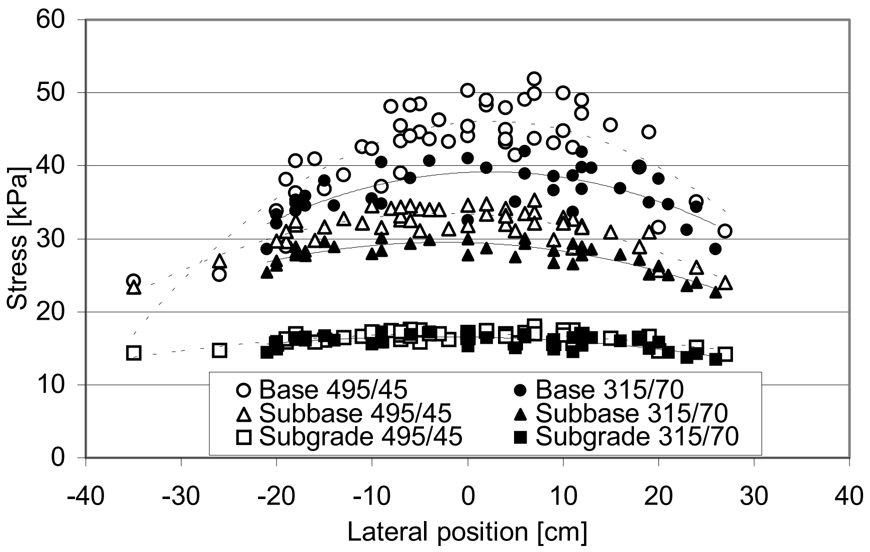


Figure 4.49- Stresses in road structure at 80 km/h.

Measurement of the asphalt strains at 80 km/h (Figure 4.50) show that the wide base single tyre (495/45R22.5) produces about 17 percent greater maximum strains (113 versus 96 µm/m) at the bottom of the 150 mm thick asphalt layer. The wider dual tyre assembly distributes the load more evenly.

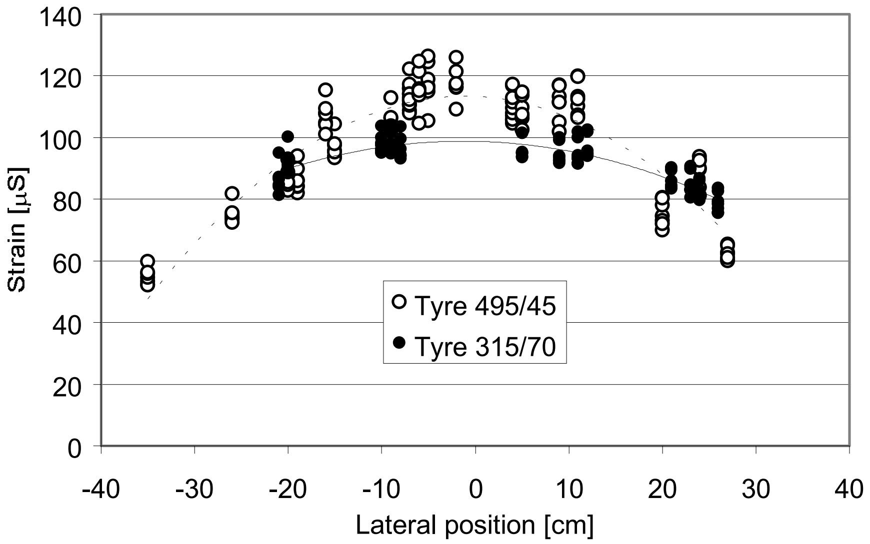


Figure 4.50 - Longitudinal strains in the bottom of the asphalt layer due to 495/45 single tyre and 315/70 dual tyre at 80 km/h. All seven sensors.

4.5.8 Results from Dutch numerical simulation of lateral wander effects

Within the framework of COST334 TG3, the Dutch Ministry of Transport, Public Works and Water Management commissioned a numerical simulation of the effects of lateral wander for several tyres and wheel loads (Nagelhout et al. 2000). VEROAD (Hopman 1999) was used to determine the stresses, strains and displacements in a multilayer visco-elastic pavement structure loaded by different wheel loads. TWINWHEELS (van

Dommelen 2000) was used to determine the effects of lateral wander and of unequal load sharing between the tyres of dual wheels.

A pavement of medium asphalt thickness was modelled, as specified in Table 4.29. In the VEROAD calculations, the granular layer and the subbase were modelled as linear-elastic materials. To calculate the stresses and strains in the granular layer and the subbase, the asphaltic layer was modelled as a linear-elastic material, using the E and ν values from Table 4.29. To calculate the permanent deformation in the asphaltic layer, the asphaltic layer was modelled as a linearly visco-elastic material, using the Burgers' model (see Nagelhout et al. 2000) and the η_1 value from Table 4.29.

Table 4.29 - Medium pavement structure for simulation of lateral wander effects

Layer	Thickness [mm]	Young's modulus (E) [MPa]	Poisson's ratio (ν) [-]	Viscosity of serial linear damper in Burgers' model (η_1) [MPa.s]
Asphalt layer	200	7500	0.40	1000
Granular layer	250	200	0.30	
Subbase		70	0.30	

The permanent displacements and strains of the medium pavement construction were calculated underneath the wheel loads, which are described in Table 4.30. These wheel loads were modelled at a travelling speed of 20 m/s (72 km/h).

Table 4.30 - Description of wheel loads

Tyre type and size	Axle load [kN]	Tyre pressure [bar]	Contact area width [mm]	Contact area length [mm]	Average contact stress [bar]
Dual tyre 295/60R22.5	115	10.0	259	174	6.38
Dual tyre 315/80R22.5	90	6.5	255	185	4.77
Dual tyre 315/80R22.5	115	8.0	255	193	5.84
Wide single tyre 385/65R22.5	90	10.0	283	201	7.90
Wide single tyre 495/45R22.5	90	8.0	428	176	5.97
Wide single tyre 495/45R22.5	115	10.0	428	180	7.46

The contact areas of the different tyres are approximately rectangular, but the VEROAD-software allows only circular loads. The rectangular loads are therefore modelled by a number of circular loads to simulate the rectangular contact area, as shown in Figure 4.51.

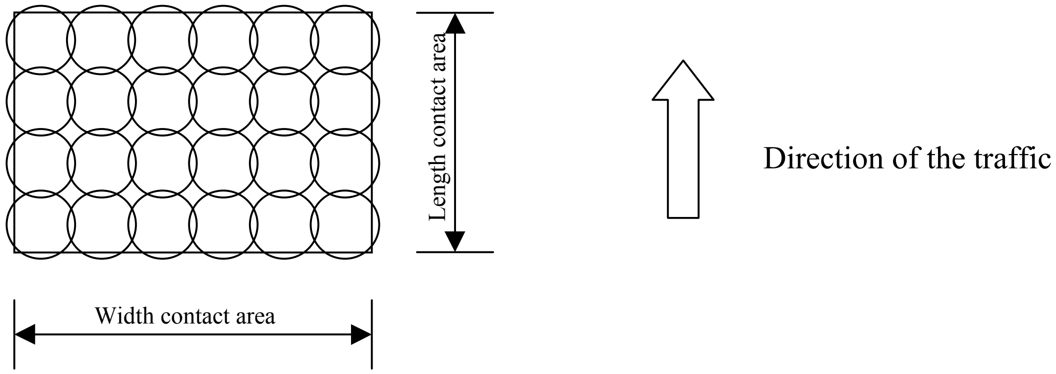


Figure 4.51 - Example of modelling rectangular contact area

The transverse profiles of the permanent deformation in the asphaltic layers were calculated, as well as the transverse profiles of the horizontal strains at the bottom of the asphaltic layer, and the vertical strains at the top of the subbase.

These profiles were then input in TWINWHEELS. This spreadsheet first calculates transverse profiles of displacements, stresses and strains due to a dual tyre, by linear superposition of the profiles of the individual tyres. Then it calculates a transverse profile of a measure of damage by raising the strains to the n^{th} power. For asphalt strain (governing fatigue) the value n=5 was chosen, for the subbase strain (governing secondary rutting) the value n=4 was used. The transverse profile of the permanent deformation in the asphaltic layers does not need any conversion, as it already represents a distress profile.

Then, lateral wander is simulated by superposition of many of these transverse profiles, each shifted sideways according to the lateral wander distribution. This distribution was input as a Laplace distribution of the tyre centres, with a lambda value of 0.12 m (corresponding with a standard deviation of 0.17 m.

The pavement wear factors for lateral distribution were determined by dividing the maximum damage with lateral wander by the maximum damage without lateral wander. These results are listed in Table 4.31. (The factors for transversal asphalt strain are given for completeness, but these are irrelevant as the longitudinal asphalt strain was shown to be the dominant parameter regarding fatigue cracking.) A factor of 0.50 means that a certain amount of laterally wandering passages of this tyre configuration produces half as much damage at the most distressed point as the same amount of passages of this tyre configuration when all pass at the same lateral position. The lower the factor, the more beneficial the effect of lateral wander. The table shows that lateral wander has a beneficial effect for all tyres considered. This effect is lowest for the subbase strain (governing secondary rutting), and highest for the rut depth (primary rutting). For primary rutting, the beneficial effect is higher for the dual tyres than for the wide base singles, that were modelled. For secondary rutting, and especially for fatigue, lateral wander has a higher beneficial effect for the wide base tyres than for the dual tyres.

Table 4.31 - Pavement wear factors for lateral distribution

Tyre size	Factor for lateral distribution based on			
	rut depth	asphalt strain		subbase strain
		longitudinal	transversal	
295/60R22.5 115 kN axle	0.50	0.84	0.66	0.84
315/80R22.5 90 kN axle	0.49	0.84	0.62	0.84
315/80R22.5 115 kN axle	0.49	0.83	0.66	0.84
385/65R22.5 90 kN axle	0.52	0.63	0.48	0.80
495/45R22.5 90 kN axle	0.62	0.69	0.60	0.81
495/45R22.5 115 kN axle	0.62	0.69	0.60	0.81

4.5.9 Results from Portuguese numerical simulation on different tyre types and lateral wander

4.5.9.1 Introduction

Within the framework of COST 334 TG3, the Laboratório Nacional de Engenharia Civil (LNEC) performed a research program on numerical simulations of primary rutting (Quaresma et al. 2000), as part of the Portuguese contribution to COST 334. The finite element computer program CREEPN (Batista 1998), developed at LNEC, was used for the calculations, using a Burgers' model for the visco-elastic modelling of the behaviour of the asphaltic materials.

In the first stages of this research, the results of the CREEPN program were compared to results of the VEROAD visco-elastic multi-layer program (Hopman 1999), and the DIANA finite element program. This yielded good agreement. Furthermore, the results of CREEPN were calibrated against experimental results. These consisted of laboratory wheel tracking tests, and of the full scale pavement performance tests at LCPC and TRL, described by Gramsammer et al (1998) and Halliday et al (1997). These full scale tests compared a prototype extra-wide base single tyre (495/45R22.5) to a dual tyre (10R22.5) at equal loads and inflation pressures.

In the laboratory wheel tracking test, deformation rates between 0.235 and 0.292 µm/cycle were measured at 60°C under a tyre pressure of 0.9 MPa. For those conditions, CREEPN predicted deformation rates between 0.217 and 0.376 µm/cycle. The variation is caused by variation in the characteristics of the material from the wheel tracking test, measured in a unconfined cyclic uniaxial creep test at the same temperature and contact stress. There is a good agreement between the predicted and measured deformation rates.

The predicted deformation rates for the full scale pavement performance tests were about 200% and 60% of the measured values, respectively for the tests at LCPC and TRL. It should be noted, however, that no material of the actually tested pavements was available to determine the material characteristics. Therefore, the CREEPN input was determined later on similar materials. Both full scale tests showed that the permanent deformation is similar for both tested tyres. The CREEPN calculations show that the permanent deformation for the two tyres are similar but a slightly higher value for the extra-wide base single tyre (495/45R22.5) was obtained in the simulation of the LCPC tests, whereas the test produced a slightly lower value for this tyre.

4.5.9.2 Numerical model

Table 4.32 shows the load characteristics (tyre contact area and contact pressure) that were used in CREEPN.

Table 4.32 – Load characteristics for LNEC calculations (based on Penant 1999)

Tyre code	Axle load (tonne)	Inflation pressure (bar)	Width (mm)	Length (mm)	Contact stress (kPa)	Ratio contact/inflation (%)
295/60R22.5	9.0	8	259	170	501.1	63.9
295/60R22.5	11.5	10	259	174	625.6	63.8
295/80R22.5	9.0	7	244	194	466.1	67.9
315/80R22.5	9.0	6.5	255	185	467.7	73.4
315/80R22.5	11.5	8	255	193	572.9	73.0
385/65R22.5	9.0	10	283	201	775.8	79.1
495/45R22.5	9.0	8	428	176	585.8	74.7
495/45R22.5	11.5	10	428	180	731.9	74.6

Four pavement structures were modelled, as shown in Figure 4.52. Thicknesses and material characteristics conform to Table 4.6. A Poisson ratio of 0.35 was used for the granular layers and the foundation, and a viscosity of 3000 MPas for the Burgers' serial damper in the characterisation of the asphaltic layers. Each simulation (combination of load and structure) was done for one pass of the load at a speed of 13.89 m/s (50 km/h).

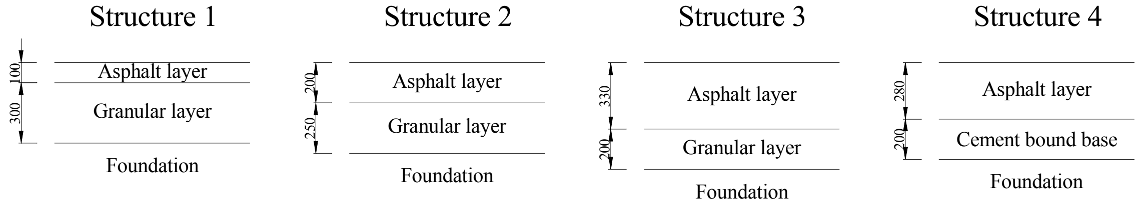


Figure 4.52 - Pavement structures modelled in CREEPN

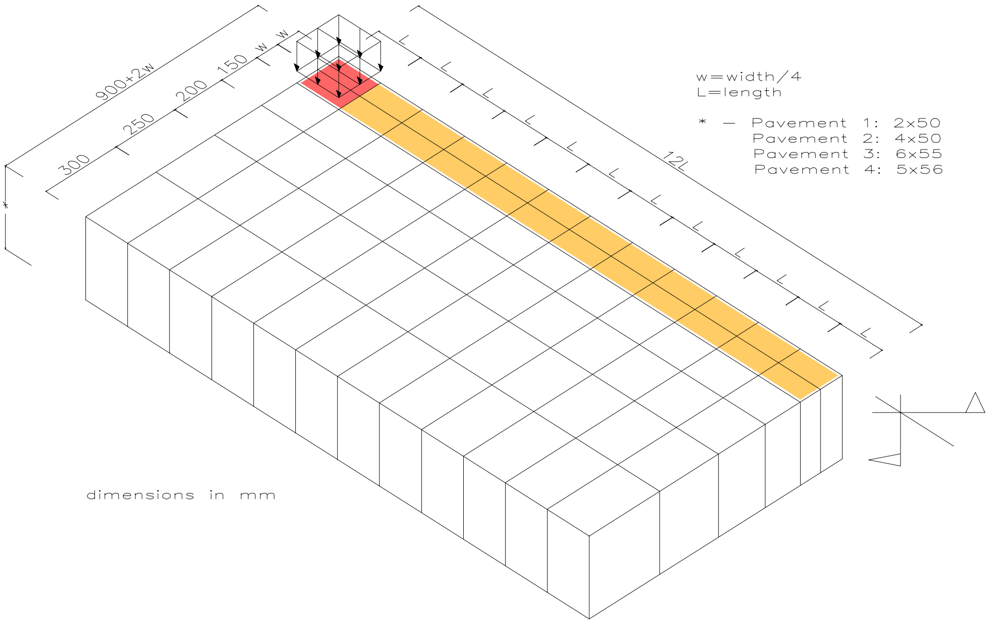


Figure 4.53 – Finite element mesh used in CREEPN

Figure 4.53 shows the finite element mesh for CREEPN (only asphalt layers). All nodes at the bottom of the mesh are fixed (no deformation allowed) and the nodes at the side edge of the mesh are fixed only in the perpendicular direction.

To take lateral wander into account, a modified Laplace distribution was used, according to

$$f(x) = \frac{1}{2\lambda} e^{-\left|\frac{x}{\lambda}\right|} \times C$$

where λ=0.08 and C=4000. This is shown in Figure 4.54. (Note that this value for lambda is smaller than those used in sections 4.5.4 and 4.5.5, indicating a more narrow distribution.)

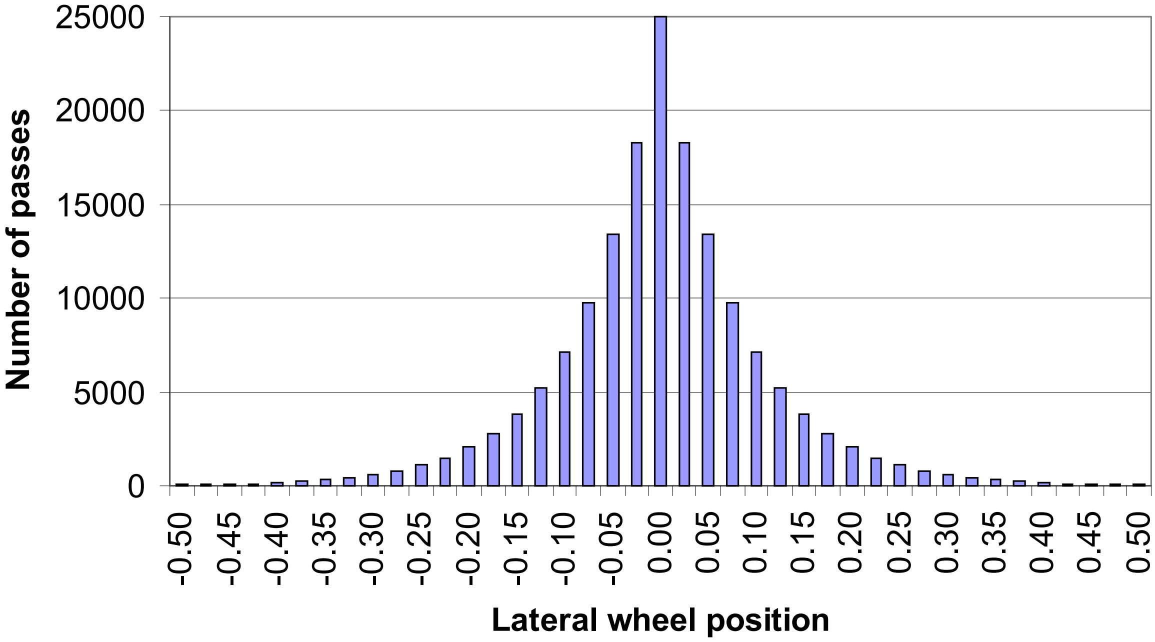


Figure 4.54 - Laplace distribution for lateral wandering (λ=0.08)

4.5.9.3 Simulation results, influence of tyre type

Figure 4.55 shows the permanent deformation parameters that were calculated using CREEPN. Only the results for the practical rut depth are presented in Table 4.33 and Table 4.34, without and with the effects of lateral wander. The latter values are also presented in Table 4.35 as pavement wear ratios, relative to the 315/80R22.5 dual tyre at 11.5 t and 8 bar, on structure 2. The effect of lateral wander is calculated by dividing the values from Table 4.34 by those of Table 4.33. The results are shown in Table 4.36.

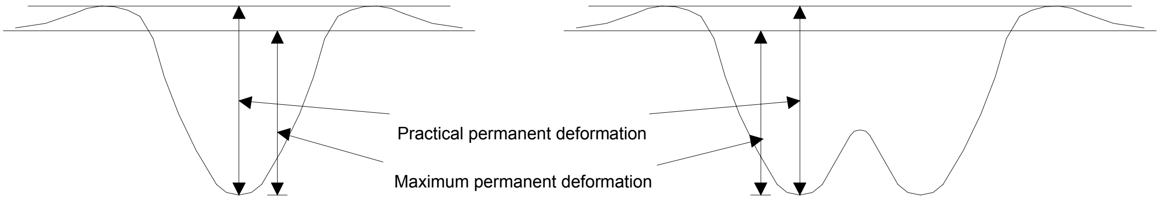


Figure 4.55 - Parameters, calculated using CREEPN

Table 4.33 - Practical permanent deformation at surface without lateral wander (µm/cycle)

Tyre configuration		Struct. 1	Struct. 2	Struct. 3	Struct. 4
295/60R22.5 (9.0 t / 8 bar)	Dual	0.127	0.240	0.380	0.329
295/60R22.5 (11.5 t / 10 bar)	Dual	0.160	0.308	0.486	0.421
295/80R22.5 (9.0 t / 7 bar)	Dual	0.137	0.253	0.395	0.343
315/80R22.5 (9.0 t / 6.5 bar)	Dual	0.130	0.243	0.384	0.333
315/80R22.5 (11.5 t / 8 bar)	Dual	0.167	0.311	0.490	0.425
385/65R22.5 (9.0 t / 10 bar)	Single	0.230	0.467	0.721	0.637
495/45R22.5 (9.0 t / 8 bar)	Single	0.149	0.305	0.517	0.440
495/45R22.5 (11.5 t / 10 bar)	Single	0.191	0.389	0.660	0.563

Table 4.34 - Practical permanent deformation at surface with the effect of lateral wander (µm/cycle)

Tyre configuration		Struct. 1	Struct. 2	Struct. 3	Struct. 4
295/60R22.5 (9.0 t / 8 bar)	Dual	0.088	0.187	0.317	0.268
295/60R22.5 (11.5 t / 10 bar)	Dual	0.114	0.240	0.404	0.342
295/80R22.5 (9.0 t / 7 bar)	Dual	0.092	0.193	0.322	0.272
315/80R22.5 (9.0 t / 6.5 bar)	Dual	0.089	0.188	0.319	0.269
315/80R22.5 (11.5 t / 8 bar)	Dual	0.115	0.241	0.407	0.343
385/65R22.5 (9.0 t / 10 bar)	Single	0.162	0.355	0.572	0.494
495/45R22.5 (9.0 t / 8 bar)	Single	0.114	0.262	0.451	0.381
495/45R22.5 (11.5 t / 10 bar)	Single	0.146	0.336	0.575	0.488

Table 4.35 - Pavement wear ratios for primary rutting, including the effect of lateral wander, relative to 315/80R22.5 dual tyre at 11.5 t and 8 bar, on structure 2

Tyre configuration		Struct. 1	Struct. 2	Struct. 3	Struct. 4
295/60R22.5 (9.0 t / 8 bar)	Dual	0.37	0.78	1.32	1.11
295/60R22.5 (11.5 t / 10 bar)	Dual	0.47	1.00	1.68	1.42
295/80R22.5 (9.0 t / 7 bar)	Dual	0.38	0.80	1.34	1.13
315/80R22.5 (9.0 t / 6.5 bar)	Dual	0.37	0.78	1.32	1.12
315/80R22.5 (11.5 t / 8 bar)	Dual	0.48	**1.00**	1.69	1.42
385/65R22.5 (9.0 t / 10 bar)	Single	0.67	1.47	2.37	2.05
495/45R22.5 (9.0 t / 8 bar)	Single	0.47	1.09	1.87	1.58
495/45R22.5 (11.5 t / 10 bar)	Single	0.61	1.39	2.39	2.02

Table 4.36 - Relative effect of lateral wander on primary rutting (distress reduction factor due to lateral wander, relative to non-wandering loading)

Tyre configuration		Struct. 1	Struct. 2	Struct. 3	Struct. 4
295/60R22.5 (9.0 t / 8 bar)	Dual	0.69	0.78	0.83	0.81
295/60R22.5 (11.5 t / 10 bar)	Dual	0.71	0.78	0.83	0.81
295/80R22.5 (9.0 t / 7 bar)	Dual	0.67	0.76	0.82	0.79
315/80R22.5 (9.0 t / 6.5 bar)	Dual	0.68	0.77	0.83	0.81
315/80R22.5 (11.5 t / 8 bar)	Dual	0.69	0.77	0.83	0.81
385/65R22.5 (9.0 t / 10 bar)	Single	0.70	0.76	0.79	0.78
495/45R22.5 (9.0 t / 8 bar)	Single	0.77	0.86	0.87	0.87
495/45R22.5 (11.5 t / 10 bar)	Single	0.76	0.86	0.87	0.87

When the PWR are calculated for each structure, relative to the 315/80R22.5 dual tyre at 11.5 t and 8 bar on the same structure, the results are almost the same for all structures listed for pavement 2 in Table 4.48. (Differences are probably due to calculation accuracy, but also could indicate physical differences.) Ratios between different pavement structures for the same load conditions are almost constant and almost equal to the ratios of asphalt thickness.

The effects of lateral wander for the dual tyres considered are all very similar and close to those for the 385/65R22.5. The effects of lateral wander for the 495/45R22.5 are smaller than for the other tyres (numbers closer to one, hence less distress reduction due to lateral wander). This is in agreement with the results of section 4.5.8. The distress reduction factors found here for the medium pavement are closer to one (indicating less reduction) than in section 4.5.8, which can be attributed to the more narrow distribution of lateral wander used here.

The beneficial effects of lateral wander for all tyres increase with decreasing pavement thickness.

4.5.9.4 Simulation results, tyre inflation pressure and size of the contact area

A parametric study with CREEPN yielded the conclusion that the permanent deformation rate for a given pavement and load magnitude was not influenced by the footprint length, but only by the footprint width. Therefore, the results of the previous section were also presented by load per tyre width, shown in Figure 4.56.

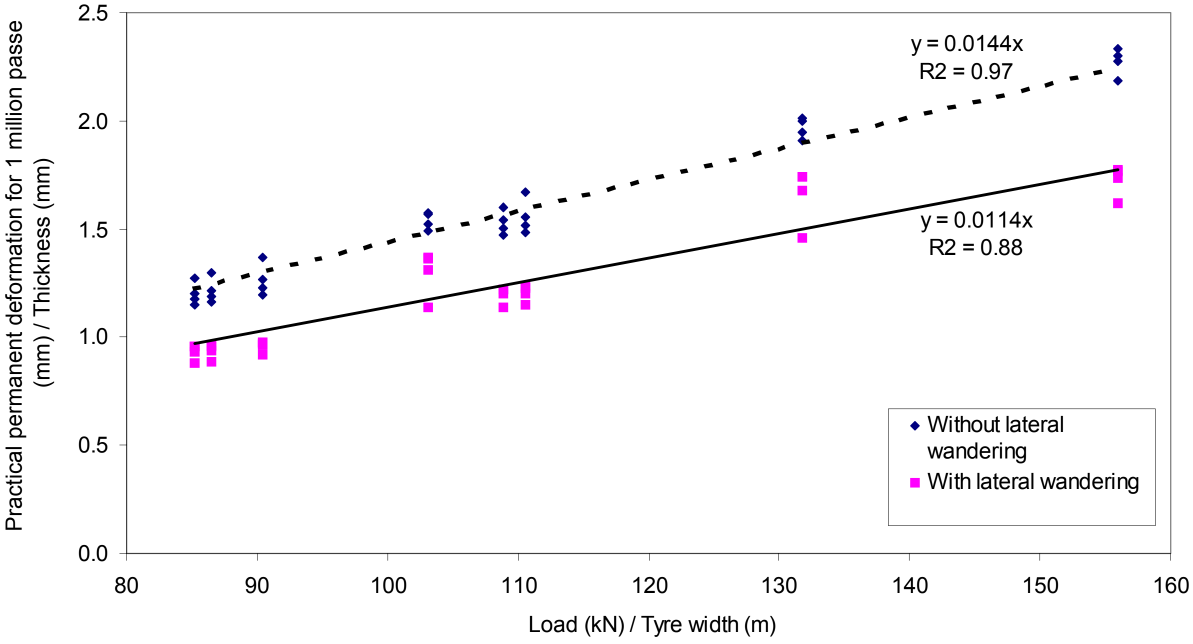


Figure 4.56 - Relation between practical permanent deformation rate, thickness of visco-elastic layers and load configuration for different tyres and structures.

This leads to the following formula for the tyre configuration factor:

$$f_{tyre\ configuration} = \frac{\dfrac{P \times h}{w}}{\left[\dfrac{P \times h}{w}\right]_{ref}}$$

where P is the wheel load, h is the thickness of asphaltic material and w is the width of the tyre footprint.

4.5.10 Results of regression analysis: formulae for relative wear effects of individual tyre types for individual distress modes under ideal conditions

4.5.10.1 Introduction

Within the framework of COST334 TG3, the Dutch Ministry of Transport, Public Works and Water Management commissioned a regression analysis on the Pavement Wear Ratio data collected by TG3 (Groenendijk 2000). The analysis aimed to determine a model for the influence of several tyre parameters on the distress development of pavement structures. TG3 requested specific model recommendations for pavement types that are relevant for the European primary and secondary road network.

4.5.10.2 Data set

The data set was assembled from the experimental data on relative pavement wear, gathered by TG3. The raw data were presented in the previous parts of section 4.5 of this report. The data set used in the regression analysis is printed in annex II of this report. This data set did not result from one, coordinated research effort with appropriate experimental design. Only the COST 334 tests were subject to such coordinated experimental design. The other results depended on what was available in literature. Therefore, some potential explanatory variables may be lacking in the data set (or subsets thereof), or may not vary sufficiently to assess their influence. Also, inter-researcher variation may exist, due to differences in testing and measuring methods. Therefore, the resulting regression models also may have some deficiencies.

Each experiment (one researcher, comparing several tyres, generally at equal axle load but possibly at different inflation pressures, at one pavement) constitutes a 'cluster' of data. Within each cluster, one tyre (mostly a dual tyre) was arbitrarily designated the 'reference' tyre. The relevant parameters of the other tyres were then expressed as relative values: the parameter value for the other tyre divided by the parameter value for the 'reference' tyre. (In the data set, the headings for these relative parameters all start with "relative".). Similarly, the amount of pavement distress caused by the other tyres also were expressed as relative values: 'pavement wear ratios' (PWR). For primary rutting these PWR are actually 'distress ratios' (PWR_D): the amount of distress caused by a tyre divided by the amount of distress for the 'reference' tyre (at equal number of load repetitions). Most PWR data on secondary rutting and fatigue are actually 'life ratios' (PWR_L), being the life of a pavement until a chosen amount of distress caused by a tyre, divided by the life of an identical pavement until the same amount of distress caused by the 'reference' tyre.

The 'reference' tyre was a different one for each experiment. A 'fixed reference' (one tyre at specific conditions) for all experiments was not possible as no distress values for such a 'fixed reference' were available from the individual experiments. (Such distress values would also be highly influenced by the pavement tested, and/or the test temperature.)

The pavement wear ratios for primary rutting were all determined in performance tests, incorporating lateral wander. (Therefore these values did not need corrections for lateral wander.) Therefore, these values are ratios of actually observed distress levels at close-to-reality conditions. So they have a high level of confidence, as no corrections or extrapolations were needed.

Most pavement wear ratios for fatigue and secondary rutting were determined from response tests, based on the measurement of maximum stresses and strains in the pavement. The pavement wear ratios were calculated from these maximum stresses and strains, using generally accepted performance relations. (These performance relations may differ between experiments, as individual researchers used the relations most applicable to their materials and conditions.) Furthermore, a correction was calculated for the effect of the lateral wander of traffic. Because of both these calculations, the confidence level of the resulting pavement wear ratios depends on the confidence level in the calculation models used.

The parameter headings in the data set have the following meaning:

- "Relative X" indicates the value of parameter X for a tyre divided by the value of X for the 'reference' tyre in the same experiment.
- "Pressure" is the actual tyre inflation pressure during the experiment.
- "Width" is the footprint width for wide base singles. For dual tyres the "width" is taken as twice the footprint width of the individual tyres. (All width values consider footprint (tyre contact area envelope) width, not tyre section width.)
- "Total width" is the footprint width for wide base singles. For dual tyres the "total width" is taken as twice the footprint width of the individual tyres plus the spacing between the footprints of the dual. This spacing was taken to be 100 mm for all duals.

- “Pressure ratio” is a factor indicating over- or underinflation of the tyre relative to the recommended pressure at that load level. This is a measure of the uniformity of the vertical contact stress distribution. (Relative overinflation generally gives higher stresses near the tyre centre, underinflation generally gives higher stresses near the tyre edge.) The pressure ratio is calculated as (actual tyre pressure) / (recommended tyre pressure + 100 kPa). The addition of 100 kPa to the recommended tyre pressure is to account for the fact that in practice tyres often are hot, which increases the pressure by about 100 kPa from their cold value. In most experiments in the data set, the speeds were so low that no significant pressure increase is likely.
- “Pavement type” is 1, 2 or 3, indicating thin, medium or thick pavements respectively (asphalt thickness around 100 mm, 200 mm and 330 mm)
- “Relative ratio for effect of lateral wander” indicates the reduction of distress because of lateral wander, expressed as the relative influence of lateral wander for a specific tyre, relative to the influence of lateral wander for the reference tyre. (When a wide base tyre is compared to a dual, this is the ratio of the beneficial effect of lateral wander for the wide base tyre over the beneficial effect of lateral wander for the dual tyre.) This is a correction factor for the pavement wear ratios.

4.5.10.3Basic statistical analysis

As a first step, the number of cases in the data set were determined, distinguished by distress mode. The results are shown in Table 4.37. This shows that only few experiments are available for secondary rutting, especially for pavements of medium thickness. It also shows that almost all data on primary rutting are for thick pavements, with one exception (a medium pavement).

Table 4.37 - Number of cases in data set, distinguished by distress mode

	Primary rutting (in asphaltic layers)	Secondary rutting (in subgrade or granular layers)				Fatigue			
	Pavement type 3 mainly, one type 2	Pavement type				Pavement type			
		All	1	2	3	All	1	2	3
# Reference tyres (= # experiments)	13	13	4	4	5	24	8	9	7
# Non-reference tyres	17	34	15	10	9	43	16	15	12
Total cases	30	47	19	14	14	67	24	24	19

Pavement type 1, 2 or 3 indicate thin, medium or thick pavements respectively (asphalt thickness around 100 mm, 200 mm and 330 mm)

As a second step, the variance of the pavement wear ratios, corrected for lateral wander, were determined. The results are shown in Table 4.38. This clearly shows that there is considerable difference in pavement wear ratio values for fatigue and secondary rutting over the pavement types. The thinnest pavements have highest pavement wear ratios. (This is in agreement with engineering knowledge, based on St Venant’s principle.) This warrants separate analysis per pavement type, where possible.

Table 4.38 - Variance of pavement wear ratios in data set

	Primary rutting	Secondary rutting				Fatigue			
	Pavement type 3 mainly, one type 2	Pavement type				Pavement type			
		All	1	2	3	All	1	2	3
Minimum	0.70	0.85	0.85	0.88	0.98	0.97	1.75	1.12	0.97
Maximum	2.45	5.57	5.57	2.70	1.10	7.33	7.33	3.60	1.35
Mean	1.40	2.02	2.98	1.47	1.02	1.91	2.71	1.72	1.07
Standard deviation	0.50	1.39	1.59	0.58	0.04	1.13	1.40	0.61	0.11

As a third step, the correlation was determined between the potentially explanatory variables considered. This analysis is not reported here. Summarising these results can be stated that many of the explanatory variables are highly correlated. Many correlations are logical from a physical point of view. (For example: as the contact area equals the width times the length, these parameters are necessarily correlated.) It is observed however, that the coefficients of correlation differ considerably between the data subsets (distress modes and / or pavement thicknesses).

4.5.10.4Regression analysis methodology

The following formula was used for the determination of the pavement wear ratio PWR of a tyre relative to a 'reference' tyre:

$$\mathbf{PWR} = f_{\text{tyre type}} * f_{\text{pressure}} * f_{\text{width}} * f_{\text{diameter}} * f_{\text{pressure ratio}} * f_{\text{contact area}} * f_{\text{total width}} * f_{\text{length}} * err$$

in which *err* is an error term, and the remaining symbols have the following meaning:

Table 4.39 - Variables in regression model

Symbol	Variable	Variable
$f_{\text{tyre type}}$	(tyre type)^a	(tyre type)^a
f_{pressure}	(pressure / pressure ref)^b	(relative pressure)^b
f_{width}	(width / width ref)^c	(relative width)^c
f_{diameter}	(diameter / diameter ref)^d	(relative diameter)^d
$f_{\text{pressure ratio}}$	(pressure ratio / pressure ratio ref)^e	(relative pressure ratio)^e
$f_{\text{contact area}}$	(contact area / contact area ref)^f	(relative contact area)^f
$f_{\text{total width}}$	(total width / total width ref)^g	(relative total width)^g
f_{length}	(length / length ref)^h	(relative length)^h

tyre type = 1 for dual tyres, and tyre type = e for (wide base) single tyres, hence ln (tyre type) = 0 for dual tyres, and ln (tyre type) = 1 for single tyres.

The other parameters are explained in section 2.2.

Reworking of the above formula by taking natural logarithms gives:

$$\begin{aligned}\ln \text{PWR} = {} & a \ln(\text{tyre type}) + b \ln(\text{relative pressure}) + c \ln(\text{relative width}) + \\ & d \ln(\text{relative diameter}) + e \ln(\text{relative pressure ratio}) + f \ln(\text{rel. contact area}) \\ & + g \ln(\text{relative total width}) + h \ln(\text{relative length}) + \ln err\end{aligned}$$

By performing linear regression analysis on the above formula, the constants a-h may be determined. Some of these constants may be 0, which does not necessarily imply that the corresponding factor has no influence on pavement distress! It may be that the data set does not supply enough information (parameter variation) to determine the influence. It also may be that the parameter is strongly correlated to other parameters, and that its influence is 'hidden' in the contribution of those other parameters to the resulting model.

The error term includes measurement errors in the data on which the model is based, as well as 'lack of fit' of the model (because of non-incorporation of unknown influential factors).

The 'Pavement wear ratio' formula given above is part of a formula for a Tyre Configuration Factor (TCF), giving the relative pavement wear for different tyre sizes at equal load. The TCF also comprises factors for tyre characteristics regarding dynamic force transmissibility, and for potential load imbalance (difference in tyre load between the tyres of a dual tyre assembly). These latter factors are not included in the present analysis. Also excluded from the present analysis are factors regarding the influence on pavement wear resulting from the axle configuration (single axle, tandem axle or tri-axle configuration), from the vehicle suspension (steel leaf springs, air suspension, etc.), or from different axle loads. Although this latter factor was not the objective of this analysis, it does influence the analysis results when pavement wear is compared due to tyres with different loads.

Regression analysis was executed on several subsets of the data, distinguishing between the three distress modes, and the data pertaining to these modes. For fatigue and secondary rutting, analysis was executed on subsets pertaining to different pavement types (thicknesses).

For each comparative experiment, two lines of data are included in the database. For regression analysis this would constitute two data points and two degrees of freedom. However, in reality only one degree of freedom exists, being the ratio or difference between the two tyres compared. One of these was arbitrarily designated as the 'reference tyre' for the comparative experiment. By definition, the pavement wear ratio and all explanatory relative values for such a reference tyre equal 1 (and hence the logarithm of these values equals 0). Including these points in the regression analysis would not be correct, as this would seemingly introduce extra degrees of freedom for the analysis. Therefore, these points were filtered out.

The chosen model type requires that for a tyre with the same characteristics (identified in the model: tyre type, width, length, pressure, diameter, contact area, pressure ratio, total width) as the reference tyre, the Pavement wear ratio must equal 1. Any deviation from 1 must either be a measurement error, or the influence of any characteristics that were not included in the model. On a logarithmic scale, all data for a reference tyre are in the origin. Data for a tyre with the same characteristics also should be in the origin. Any deviation could show as an intercept in the regression model. However, such an intercept would be very impractical for application of the model. Therefore, regression analysis was performed excluding the intercept (i.e. forcing the regression through the origin).

Regression analysis was performed using 'stepwise' analysis. This means that first the most significant variable is included in the regression model. Then, in successive steps, the next most significant variable is added when its significance is great enough, or a variable may be excluded when its significance is too low. This process was done automatically by SPSS, but its progress was monitored by the analyst, to check parameter selection for the influence of small differences in significance, and to guard against second-order effects, where one parameter functions as a 'correction' term for another parameter. (The data set was not considered sufficiently complete and consistent to determine such 'corrections' with sufficient confidence.)

4.5.10.5Regression results primary rutting

The preferred model for primary rutting is model:

$$\text{PWR} = (\text{rel. width})^{-1.68} * (\text{rel. pressure ratio})^{0.81} * (\text{rel. length})^{-0.85}$$

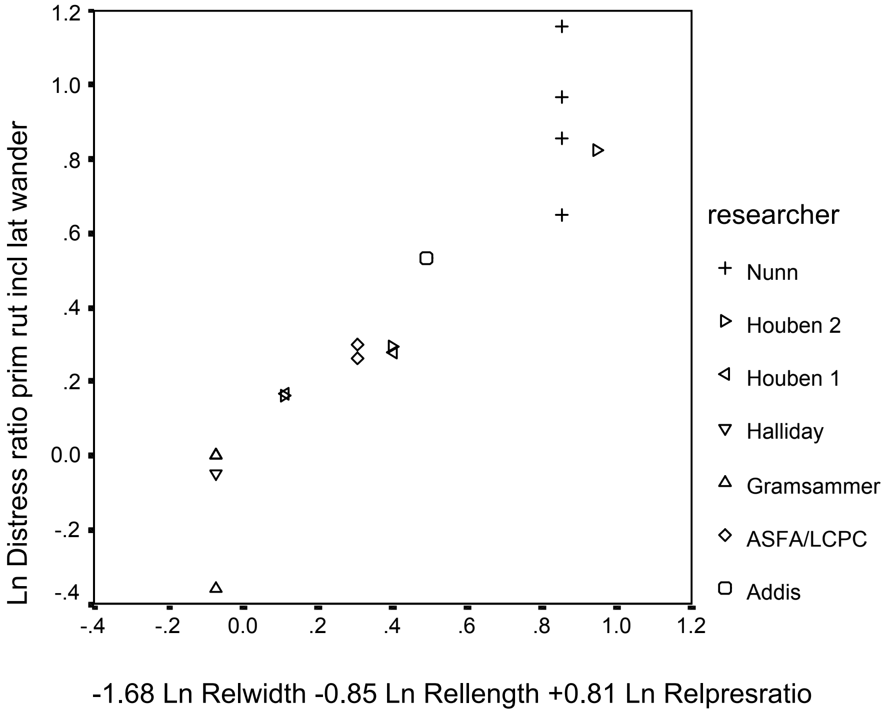
If obtaining the ‘length’ values is not feasible, one of the following models can be taken:

$$\text{PWR} = (\text{rel. width})^{-1.65} * (\text{rel. pressure ratio})^{1.42} * (\text{rel. diameter})^{-1.12}$$

or:

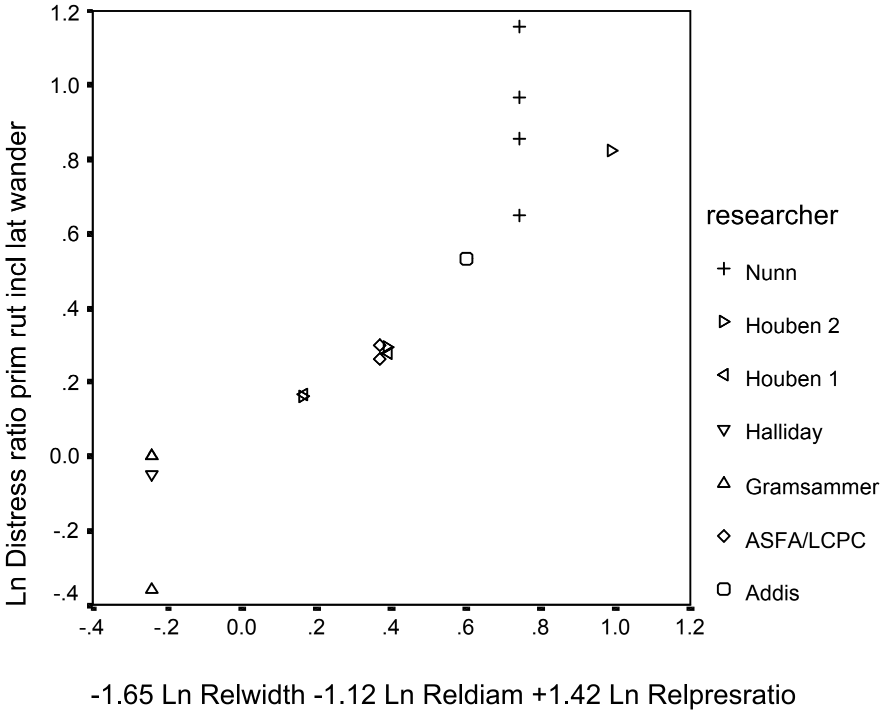
$$\text{PWR} = (\text{rel. width})^{-1.66} * (\text{rel. pressure ratio})^{1.50}$$

These models are shown in Figure 4.58 to Figure 4.59. The legend refers respectively to: Nunn (2000, see 4.5.2), Houben et al. (1999b, see 4.5.5), Houben et al. (1999a, see 4.5.5), Halliday et al. (1997, see 4.5.2), Gramsammer et al. (1998, see 4.5.2), Gramsammer et al. (1997, see 4.5.2), Blackman et al. (2000, see 4.5.4).



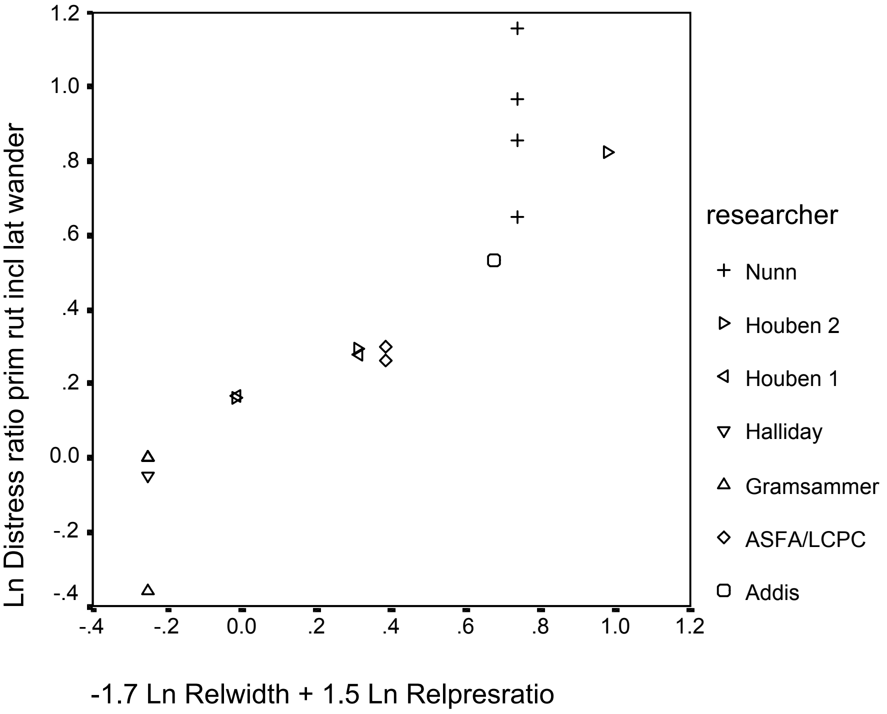
(r^2=0.93)

Figure 4.57 - Predicted versus observed PWR (logarithmic scale), primary rutting



(r^2=0.88)

Figure 4.58 - Predicted versus observed PWR (logarithmic scale), primary rutting



(r^2=0.87)

Figure 4.59 - Predicted versus observed PWR (logarithmic scale), primary rutting

4.5.10.6 Regression results secondary rutting

Pavement wear ratios for secondary rutting were dependent on pavement thickness and on the depth of measurement. Pavement wear ratios increased with decreasing pavement thickness. Also, the closer to the surface, the larger the pavement wear ratios. All pavement wear ratios for thick pavements (type 3) were very close to 1. This is all in agreement with engineering knowledge, based on St. Venant's principle. Limited attempts were made to quantify this thickness dependency, but did not succeed.

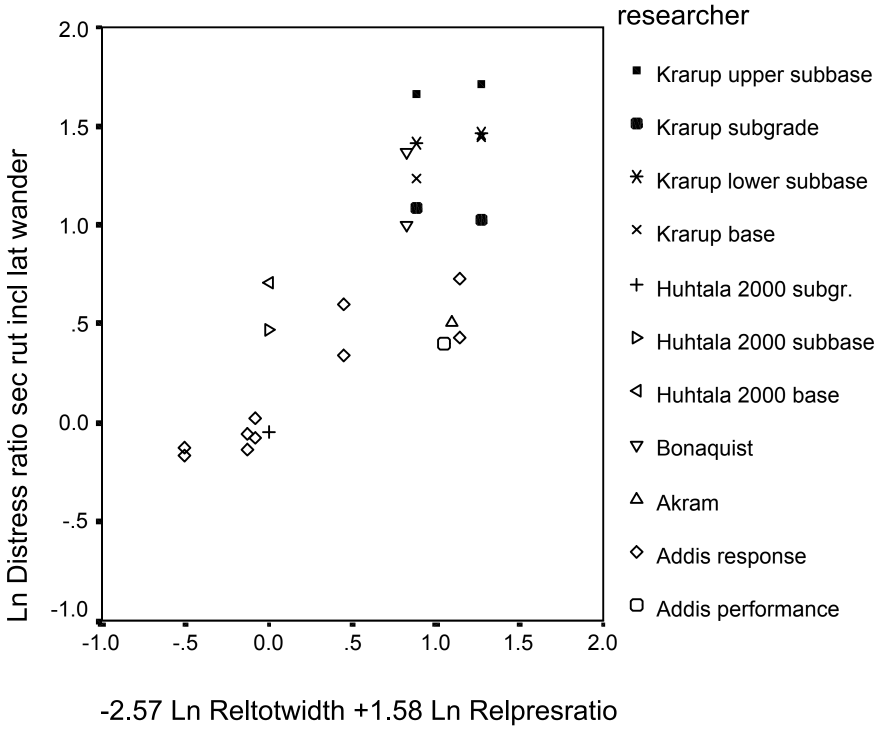
Analysis was performed on several subsets of data:

- all pavements,
- thin pavements (type 1) only,
- medium pavements (type 2) only,
- thin and medium pavements (type 1 and 2) combined.

Unfortunately, all models only had a moderate fit. The separate models for pavement types 1 and 2 were not satisfactory. Therefore, the model was chosen, derived for pavement types 1 and 2 combined. (The data for pavement type 3 should be taken separately, as these pavement wear ratios were all very close to 1, and secondary rutting is considered to be only slightly relevant for thick pavements.)

$$PWR = (\text{rel. total width})^{-2.57} * (\text{rel. pressure ratio})^{+1.58}$$

This is shown in Figure 4.60. The legend refers respectively to: Krarup (1994a, 1994b, 1995, see 4.5.2), Huhtala et al. (2000a, see 4.5.7), Bonaquist (1992, 1993, see 4.5.2), Akram et al. (1993, see 4.5.2),), Blackman et al. (2000, see 4.5.4).



(r^2=0.78)

Figure 4.60 - Predicted versus observed PWR (logarithmic scale), secondary rutting, pavement types 1 and 2 combined

4.5.10.7 Regression results fatigue (cracking)

For fatigue, separate regression analyses were executed on the following subsets:

- all data
- pavements type 1
- pavements type 2
- pavements type 1 and 2 combined.

The latter combination was included, as most pavement wear ratios for fatigue on thick pavements were very close to 1, like with secondary rutting. (Again, this is in agreement with engineering knowledge, based on St. Venant's principle.) This subset combines all remaining data.

Analysis where the regression program was free to determine the best-model produced a wide variation of selected parameters and corresponding regression coefficients. This was considered not practically feasible. Therefore, explanatory parameters were sought that would provide a reasonable fit for all different pavement thicknesses, although with possibly different values for the coefficients. Unfortunately, all models failed to predict the full variability of the measured range of pavement wear ratios.

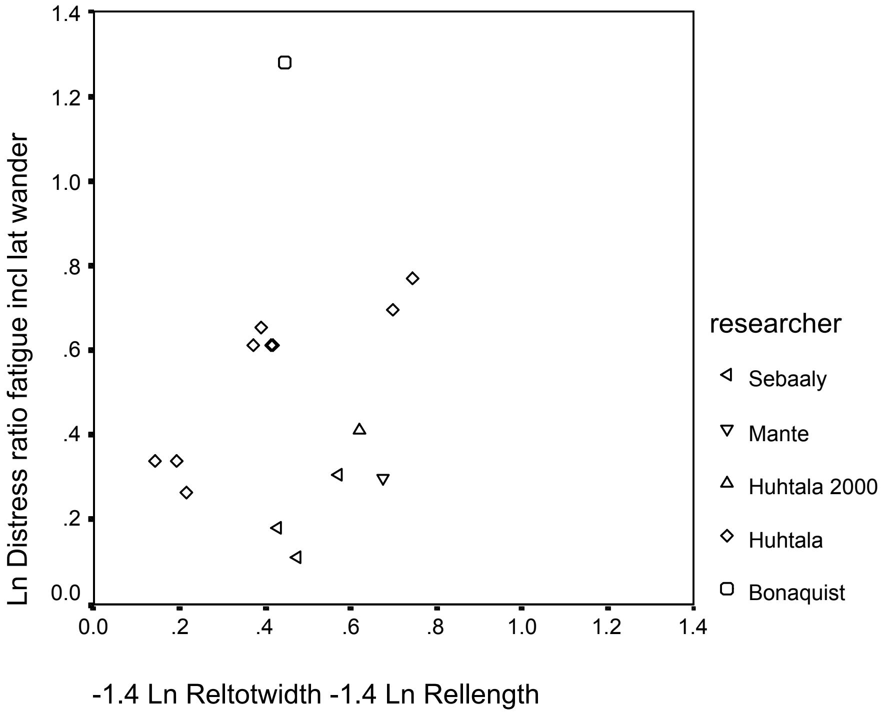
Separate models were found for the different pavement types (thicknesses). Combining pavement types did not produce better models. For the characterisation of the European secondary road network, the following model for pavement type 2 was chosen:

$$\text{PWR} = (\text{rel. total width})^{-1.36} * (\text{rel. length})^{-1.40}$$

If obtaining the 'length' values is not feasible, the following model can be taken:

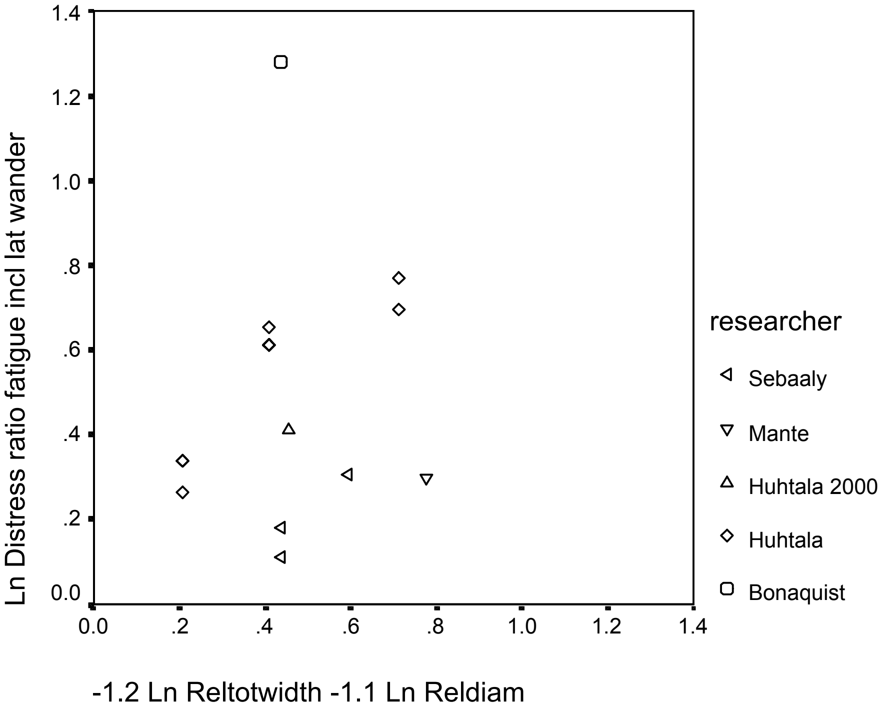
$$\text{PWR} = (\text{rel. total width})^{-1.23} * (\text{rel. diameter})^{-1.14}$$

These models are shown in Figure 4.61 and Figure 4.62. The legend refers respectively to: Sebaaly (1992, see 4.5.2), Mante et al. (1995b, see 4.5.2), Huhtala et al. (2000a, see 4.5.7), Huhtala et al. (1989, 1990, 1992, see 4.5.2), Bonaquist (1992, 1993, see 4.5.2).



(r^2=0.67)

Figure 4.61 - Predicted versus observed PWR (log scale), fatigue, pavement type 2



(r^2=0.67)

Figure 4.62 - Predicted versus observed PWR (log scale), fatigue, pavement type 2

4.5.10.8 Summary and conclusions

Regression analysis was performed to determine a model for the influence of several tyre parameters on the distress development of pavement structures. The data set was assembled from the experimental data on relative pavement wear, gathered by TG3. These data are partly based on a literature survey, and partly on experiments executed within the framework of COST 334, TG3.

Pavement wear ratios on primary rutting (i.e. in the asphaltic layers) are mainly derived from actually measured distress developments in performance tests. Most pavement wear ratios for fatigue and secondary rutting (i.e. in the granular layers and the subgrade) are based on ratios of measured stresses or strains, converted to life ratios using commonly accepted performance relations.

The pavement wear ratios for fatigue were strongly dependent on pavement thickness, and not only on tyre factors. Pavement wear ratios increased with decreasing pavement thickness. Pavement wear ratios for secondary rutting were also dependent on pavement thickness (in the same way as fatigue, but even stronger), and also on the depth of measurement. The closer to the surface, the larger the pavement wear ratios. Limited attempts were made to quantify this thickness dependency, but did not succeed. Therefore, separate analyses were made for the different pavement thicknesses. Applying the analysis results in practice, care should be taken to select the formula for the proper pavement thickness.

For primary rutting, several models were obtained, having a good fit to the data as well as being consistent with engineering knowledge. For secondary rutting and fatigue, the fit of all models was moderate to poor. For secondary rutting it was recommended to combine the data for thin and medium pavement. For fatigue, separate models were determined for thin and medium pavements.

Summarising per distress mode and pavement type, the models for the Pavement Wear Ratio (PWR) were recommended, listed in Table 4.40.

Table 4.40 - Recommended models for the Pavement Wear Ratio

	Primary rutting	Secondary rutting	Fatigue (cracking)
Thin pavements (type 1): thickness of asphaltic layers 100 mm or less	no data available, distress mechanism not considered to be relevant	PWR = (rel. total width)$^{-2.57}$ * (rel. pressure ratio)$^{+1.58}$	PWR = (rel. total width)$^{-2.88}$ * (rel. length)$^{-3.13}$ or PWR = (rel. total width)$^{-2.44}$ * (rel. diameter)$^{-2.47}$
Medium pavements (type 2): thickness of asphaltic layers around 200 mm	only one experiment available, use of model for pavement type 3 recommended		PWR = (rel. total width)$^{-1.36}$ * (rel. length)$^{-1.40}$ or PWR = (rel. total width)$^{-1.23}$ * (rel. diameter)$^{-1.14}$
Thick pavements (type 3): thickness of asphaltic layers 300 mm or more (data for primary rutting included one pavement type 2)	PWR = (rel. width)$^{-1.68}$ * (rel. pressure ratio)$^{0.81}$ * (rel. length)$^{-0.85}$ or PWR = (rel. width)$^{-1.65}$ * (rel. pressure ratio)$^{1.42}$ * (rel. diameter)$^{-1.12}$ or PWR = (rel. width)$^{-1.66}$ * (rel. pressure ratio)$^{1.50}$	PWR about equal to 1 (see Table 4.38)	PWR about equal to 1 (see Table 4.38)

The meaning of the parameters in the table above is explained in section 4.5.10.2.

The Pavement Wear Ratio formulae given above are part of a formula for a Tyre Configuration Factor (TCF), giving the relative pavement wear for different tyre sizes at equal load. The TCF also comprises factors for dynamic loads, and for potential load imbalance (difference in tyre load between the tyres of a dual tyre assembly). These latter factors are not included in the formulae above. Also excluded are factors regarding the influence of the axle configuration, the vehicle suspension, or different axle loads.

The models are only valid within the range of the (experimental) data on which they are based. This range is detailed by Groenendijk (2000). Extrapolations outside this range should be treated with utter caution, and preferably such extrapolations should be avoided altogether. The validity of the models is further indicated by their correlation coefficients, and can be visually assessed from the plots of predicted versus measured pavement wear ratios in the previous sections. The choice between different models could be made on the basis of these graphs, and/or on the basis of the availability of input data.

Although the regression coefficients are reported in two decimals, it should be noted that the second decimal has only very little significance (if at all). Small changes in the data set (e.g. due to ‘chance errors’) could sometimes even cause the first decimal to change!

4.6 EFFECTS OF UNEQUAL LOAD SHARING IN DUAL TYRE ASSEMBLIES

4.6.1 Introduction

As stated in section 4.3.6.6, generally is assumed that the wheel load is shared equally between both tyres of a dual assembly. However, this might not be true in practice. Several reasons could cause an unequal load division (‘load imbalance’) between twinned tyres:

- differences in vertical stiffness between both tyres, because of
  - differences in inflation pressure
  - different tyre structure (brand, etc.)
- differences in vertical compression between both tyres, because of
  - differences in diameter between both tyres
  - bending of the vehicle axle
  - transverse unevenness of the pavement surface

Due to the non-linear relationship between load and pavement distress, the tyre with the larger load will cause disproportional more pavement wear. Therefore an ‘imbalanced’ dual tyre assembly may cause more pavement wear than a properly ‘balanced’ dual assembly. This factor may influence the comparison of dual and single tyre assemblies.

Section 4.6 aims to quantify the pavement wear effects of this ‘load imbalance’. Section 4.6.2 gives findings from literature. Sections 4.6.3 to 4.6.6 present results of research that was specially initiated for COST 334. Finally, section 4.6.7 attempts a generalisation of these combined research findings.

4.6.2 Literature findings

No extensive literature survey was executed into the phenomenon of load imbalance. However, it was identified that Molzer (1996) had considered this subject in some detail, based on numerical modelling using the ALIZE multi-layer software (LCPC 1993). He modelled three flexible pavement types, with asphaltic layer thicknesses of 0.23, 0.16 and 0.09 m respectively, all on an unbound granular base. This base consisted of a 0.20 m thick upper layer of angular material and a 0.30 m thick lower layer of more rounded material. Tyres were modelled as circular uniformly loaded areas, with contact stresses being equal to the inflation pressure. Molzer calculated distress factors for fatigue at the bottom of the asphaltic layers, relative to a 100 kN axle load with single tyres having a contact stress of 0.7 MPa. In calculating these factors, he accounted for the yearly variations in asphalt temperature, regarding their effects both on pavement stiffness (and hence stresses and strains) and on fatigue resistance of the bituminous materials.

To characterise the load imbalance, Molzer used the ratio R_1/Q (in percent), being the load on the most heavily loaded tyre divided by the total load on the dual tyre assembly. ($R_1/Q=50\%$ indicates equal load sharing, $R_1/Q=75\%$ indicates that one tyre carries 75% and the other only 25% so one tyre carries three times as much as the other, $R_1/Q=100\%$ indicates that one tyre carries all the load, so the other is flat or even non-existing)

Molzer distinguished several influencing factors:

- different contact pressures, but equally distributed loads,
- different loads, but equal contact pressures,

- transversal unevenness of the pavement,
- centre distance of the tyres in the dual assembly.

For the theoretical case with equally distributed loads but different contact stresses, Molzer found that the maximum distress factor (at the bottom of the asphaltic layers) occurs close to the centre of the most highly inflated tyre. This maximum distress factor was found to be dependent mainly on the pressure of this most highly inflated tyre (at a certain wheel load), and almost independent of the inflation pressure of the other tyre.

For the theoretical case with unequal loads but equal contact stresses, Molzer found that the thinner pavement was less sensitive to load imbalance than the thicker pavements. He also found that the sensity to load imbalance for all pavements increases with increasing contact stress. Finally, he found that the thinner pavements are much more sensitive to the magnitude of the contact stress.

The first two factors above were investigated only as theoretical cases to differentiate the effects of load and pressure. Molzer notes that unequal inflation pressures in a dual tyre assembly not only give rise to higher contact stresses under the most highly inflated tyre, but also to increased stiffness of that tyre and higher loads on that tyre. He cites Zahnmesser (1981) who determined the load difference for (then) common radial tyre assemblies (10R20 to 13R22.5) as a function of inflation pressure difference. Zahnmesser found that $50.5\% < R_1/Q < 51\%$ for 1 bar pressure difference, and $51.2\% < R_1/Q < 52.5\%$ for 2 bar pressure difference, so a substantial difference in pressure only gives small differences in load. Molzer used worst case R_1/Q values of 55% and 57.5 in his calculations, corresponding to pressure differences of more than 3 to 4 bar, or incorporating load differences due to other factors, such as differing tyre wear.

Transverse unevenness (rutting) of the pavement may cause unequal load sharing because it may cause one tyre (outside or up the slope of the rut) to be compressed more than the other (at the bottom or down the slope of the rut), see Figure 4.15. Molzer determined the maximum difference in tyre compression Δy in mm for a dual tyre assembly with 0.34 centre distance between the tyres, on about 30 measured rut profiles. Linear regression on this data yielded $\Delta y = 0.67 * RD$, where RD is the rut depth in mm. The worst-case relation on the data was $\Delta y = 0.92 * RD$. He then again cited Zahnmesser (1981), who found that $60\% < R_1/Q < 63\%$ for $\Delta y = 20$ mm ($R_1/Q \approx 0.6 * \Delta y$). However, Molzer takes another worst case approach and uses $R_1/Q = 0.7 * \Delta y$ or $R_1/Q = 0.75 * \Delta y$. He then combines these data with a rut depth development according to $\mathrm{RD} = A + \mathrm{B} * \sqrt{\mathrm{t}}$, and calculates the time-averaged value of R_1/Q until a maximum allowable rut depth of 20 or 30 mm. For a maximum rut depth of 20 mm, he finds $R_1/Q \approx 56.8\%$, using the minimum values of his parameters above. (For 30 mm maximum rut depth, he finds $R_1/Q \approx 65\%$, using the maximum parameter values.)

Combining the load imbalance due to pressure differences and due to transverse unevenness, Molzer finds $R_1/Q \approx 62\%$ for 20 mm maximum rut depth and $R_1/Q \approx 72.5\%$ for 30 mm maximum rut depth. He then proceeds his calculations with a value of $R_1/Q \approx 75\%$ (meaning that one tyre carries three times as much load as the other).

However, this value is unrealistically high, because of the following reasons:

- because of aquaplaning dangers, the maximum allowable rut depth in Europe is generally around 20 mm, and not 30 mm,

- Molzer used worst-case assumptions for Zahnmesser's data and for inflation pressure differences,
- all calculations are based on the worst case with the maximum compression difference (one tyre at the bottom of the rut and the other high up).

Therefore, practical average values of R_l/Q are almost certainly below 60%, probably even below 55%.

The centre distance between the tyres was derived from extensive measurements by Blab (1995), yielding the distribution in Table 4.41.

Table 4.41 - Distribution of centre distances between dual tyres (Blab 1995)

Distance class	0.24-0.29 m	0.29-0.34 m	0.34-0.39 m	0.39-0.44 m
Occurrence	8 %	29 %	53 %	10 %

Molzer used this distribution, together with R_l/Q=75%, to calculate distress factors, and used a characteristic (distress-weighted average) value of 0.34 m for the centre distance between the tyres. Generally, a decrease in centre distance will produce higher maximum stresses and strains at the bottom of the asphalt, under the same total wheel load, and hence greater pavement wear.

Finally, Molzer calculated distress factors for the three chosen pavement types, using 0.34 m tyre centre distance and R_l/Q=75%, for axle loads between 20 and 115 kN. He concluded that:

- thick pavements (0.23 m asphalt) were about twice as sensitive to changes in axle load as thin pavements (0.09 m asphalt),
- thin pavements were about twice as sensitive to changes in contact stress as thick pavements.

Concluding can be stated that Molzer gives very comprehensive analyses of all relevant parameters and he provides a good methodological framework for such analyses. However, his results cannot be used directly to answer the TG3 research questions, as he compounds worst-case assumptions about the actual conditions. Hence, his results present a very extreme condition, a deliberately conservervative estimate for design purposes. Furthermore, his results are based on numerical modelling only. Therefore, TG3 decided to perform actual measurements of pavement response under unequally inflated tyres, and to do some modelling work with input values which are representative for in-service conditions. This is described in the following sections.

4.6.3 Unequal load sharing due to differences in inflation pressure, British response testing

Full scale pavement response and performance tests were carried out using TRL's Pavement Testing Facility, as part of the British contribution to COST 334 (Blackman et al. 2000). Two pavement structures were tested, one comprising an asphalt thickness of 100 mm, the other with an asphalt thickness of 200 mm. Subgrade strains were measured under six different tyre configurations at several wheel loads and inflation pressures.

The tested pavements and instrumentation were already described in section 4.5.4. The dual tyres assemblies were tested at combinations of 10 & 8 bar, 10 & 6 bar and 8 & 6 bar, besides being tested at equal inflation pressures for both tyres of 6, 8 and 10 bar. For all the tests, measurements were made with each of the tyres and the centre of the dual tyre assembly directly above the gauge line. Regardless of the inflation pressure, the peak vertical strains in the subgrade occurred when the centre of the assembly was directly above the gauge, although this may not be the case if measurements are made at or near the pavement surface. Table 4.42 and Table 4.43 show the measured peak values.

These strains were expressed as a ratio, relative to each tyre at 8 & 8 bar, and then these ratios were averaged over the three sections per pavement thickness. The resulting strain ratios are shown in Table 4.44 and Table 4.45. These tables show that the effects of unequal inflation pressure on the subgrade strain at about 0.5 m depth are practically negligible. This was to be expected due to the application of St Venant's principle. Closer to the pavement surface the differences may be higher.

Table 4.42 - Vertical subgrade strains (µm/m), 100 mm pavement, 475 mm below pavement surface

Tyre size	Inflation pressure (bar)					
	10&10	10&8	10&6	8&8	8&6	6&6
section 1						
295/60R22.5	985		993	988		973
295/80R22.5	1027	1034	1035	1045	1044	1026
315/70R22.5	935		943	939		933
315/80R22.5	997		947	955		957
section 2						
295/60R22.5	643	645	652	649	653	644
295/80R22.5	637	639	647	653	649	642
315/70R22.5	646	649	654	654	655	642
315/80R22.5	644	645	649	650	649	633
section 3						
295/60R22.5	764		765	765		754
295/80R22.5	800	802	805	794	796	778
315/70R22.5	774		773	776		753
315/80R22.5	792		789	786		764

Table 4.43 - Vertical subgrade strains (µm/m), 200 mm pavement, 575 mm below pavement surface

Tyre size	Inflation pressure (bar)					
	10&10	10&8	10&6	8&8	8&6	6&6
section 1						
295/60R22.5	332		332	332		323
295/80R22.5	309	311	309	311	310	303
315/70R22.5	311		313	312		303
315/80R22.5	313		309	312		312
section 2						
295/60R22.5	277	277	274	275	275	272
295/80R22.5	278	275	273	278	274	269
315/70R22.5	281	278	275	277	270	270
315/80R22.5	282	277	274	278	273	270
section 3						
295/60R22.5	280		275	273		272
295/80R22.5	297	293	293	290	293	289
315/70R22.5	284		277	280		274
315/80R22.5	283		283	280		280

Table 4.44 - Strain ratios, relative to each dual tyre at 8 & 8 bar, 100 mm pavement

Tyre size	Inflation pressure (bar)					
	10&10	10&8	10&6	8&8	8&6	6&6
295/60R22.5	1.00	0.99	1.00	**1.00**	1.01	0.99
295/80R22.5	0.99	0.99	1.00	**1.00**	1.00	0.98
315/70R22.5	0.99	0.99	1.00	**1.00**	1.00	0.98
315/80R22.5	1.01	0.99	1.00	**1.00**	1.00	0.98

Table 4.45 - Strain ratios, relative to each dual tyre at 8 & 8 bar, 200 mm pavement

Tyre size	Inflation pressure (bar)					
	10&10	10&8	10&6	8&8	8&6	6&6
295/60R22.5	1.01	1.01	1.00	**1.00**	1.00	0.99
295/80R22.5	1.01	1.00	1.00	**1.00**	1.00	0.98
315/70R22.5	1.01	1.00	1.00	**1.00**	0.97	0.97
315/80R22.5	1.01	1.00	1.00	**1.00**	0.98	0.99

4.6.4 Unequal load sharing due to differences in inflation pressure, French response testing

In section 4.5.6, part of the French contribution to COST 334 was described. This consisted of measurements and numerical modelling of strains at the bottom of the asphalt at the Manège de Fatigue of the LCPC under several combinations of tyres, wheel loads and inflation pressures. Among other combinations, a 315/80R22.5 dual tyre assembly was tested, at 57.5 kN wheel load and tyre pressures of 6 and 10 bar.

For the tested structure, the most severe strain occurred under the most inflated tyre and was close to the one computed under the same dual tyre assembly with the same load, but at 10 bar inflation pressure in both tyres. The pavement life would be similar in these two conditions.

As the tested pavement structure was very thick, however, and the strains were considered at a depth of 0.48 m, it was to be expected that only small differences would occur, due to the application of St Venant's principle. For thinner pavement structures, the effects of load imbalance could be expected to be larger.

4.6.5 Unequal load sharing due to differences in inflation pressure or diameter, Portuguese numerical simulation

In section 4.5.9, part of the Portuguese contribution to COST 334 was described. This consisted of numerical simulations of primary rutting (Quaresma et al. 2000) at the Laboratório Nacional de Engenharia Civil (LNEC). This research included the effects of unequal load sharing between the tyres of dual wheels. The finite element computer program CREEPN (Batista 1998), developed at LNEC, was used for the calculations, using a Burgers' model for the visco-elastic modelling of the behaviour of the asphaltic materials. The validation of the program, the modelled pavement structures, the finite element mesh used in the calculations and the lateral wander that was taken into account were detailed in section 4.5.9.

Table 4.46 shows the load characteristics (tyre contact area and contact pressure) that were used in CREEPN. For the imbalanced loads on the dual tyre assemblies (295/60R22.5, 295/80R22.5 and 315/80R22.5), a 25% higher contact pressure (relative to Table 4.46) was used for one tyre and a 25% lower contact pressure for the other tyre, keeping the load areas constant. This results in one tyre carrying 25% more load than average (i.e. 62.5% of the total wheel load), and the other 25% less (47.5% of the wheel load).

Table 4.46 – Load characteristics for LNEC calculations (based on Penant 1999)

Tyre code	Axle load (tonne)	Inflation pressure (bar)	Width (mm)	Length (mm)	Contact stress (kPa)	Ratio contact/inflation (%)
295/60R22.5	9.0	8	259	170	501.1	63.9
295/60R22.5	11.5	10	259	174	625.6	63.8
295/80R22.5	9.0	7	244	194	466.1	67.9
315/80R22.5	9.0	6.5	255	185	467.7	73.4
315/80R22.5	11.5	8	255	193	572.9	73.0

Only the results for the practical rut depth are presented in Table 4.47, including the effects of lateral wander. These values are also presented in Table 4.48 as pavement wear ratios, relative to the 315/80R22.5 dual tyre at 11.5 t and 8 bar, on structure 2.

Table 4.47 - Practical permanent deformation at surface with the effect of lateral wander (μm/cycle)

Tyre configuration		Struct. 1	Struct. 2	Struct. 3	Struct. 4
295/60R22.5 (9.0 t / 8 bar)	Balanced	0.088	0.187	0.317	0.268
	Imbalanced	0.109	0.232	0.383	0.327
295/60R22.5 (11.5 t / 10 bar)	Balanced	0.114	0.240	0.404	0.342
	Imbalanced	0.140	0.298	0.489	0.417
295/80R22.5 (9.0 t / 7 bar)	Balanced	0.092	0.193	0.322	0.272
	Imbalanced	0.114	0.240	0.390	0.334
315/80R22.5 (9.0 t / 6.5 bar)	Balanced	0.089	0.188	0.319	0.269
	Imbalanced	0.110	0.234	0.385	0.328
315/80R22.5 (11.5 t / 8 bar)	Balanced	0.115	0.241	0.407	0.343
	Imbalanced	0.142	0.300	0.492	0.419

Table 4.48 Pavement wear ratios for primary rutting, including the effect of lateral wander, relative to 315/80R22.5 dual tyre at 11.5 t and 8 bar, on structure 2

Tyre configuration		Struct. 1	Struct. 2	Struct. 3	Struct. 4
295/60R22.5 (9.0 t / 8 bar)	Balanced	0.37	0.78	1.32	1.11
	Imbalanced	0.45	0.96	1.59	1.36
295/60R22.5 (11.5 t / 10 bar)	Balanced	0.47	1.00	1.68	1.42
	Imbalanced	0.58	1.24	2.03	1.73
295/80R22.5 (9.0 t / 7 bar)	Balanced	0.38	0.80	1.34	1.13
	Imbalanced	0.47	1.00	1.62	1.39
315/80R22.5 (9.0 t / 6.5 bar)	Balanced	0.37	0.78	1.32	1.12
	Imbalanced	0.46	0.97	1.60	1.36
315/80R22.5 (11.5 t / 8 bar)	Balanced	0.48	**1.00**	1.69	1.42
	Imbalanced	0.59	1.24	2.04	1.74

From these tables can be derived that an ‘imbalance ratio’ of 0.25 (one tyre 25% more load than average, the other 25% less than average) produces an increase in primary rutting rate of 25%. This is in agreement with the fact that the asphaltic material was modelled as a linearly visco-elastic material. Generally can be concluded that an ‘imbalance ratio’ of X results in (1 + X) times as much primary rutting, according to the models used here.

4.6.6 Total effect of unequal load sharing on relative pavement wear, Dutch numerical simulation

Within the framework of COST 334 TG3, the Dutch Ministry of Transport, Public Works and Water Management commissioned a numerical simulation of the effects of unequal load sharing between the tyres of dual wheels (Nagelhout et al. 2000). VEROAD was used to determine the stresses, strains and displacements in a multilayer visco-elastic pavement structure loaded by different wheel loads. TWINWHEELS was used to determine the effects of lateral wander and of unequal load sharing between the tyres of dual wheels.

The basic data of this simulation were already described in section 4.5.8. A type 2 pavement structure (medium asphalt thickness) was modelled in VEROAD, loaded by the wheel loads, described in Table 4.49, at a speed of 20 m/s (72 km/h).

Table 4.49 - Description of wheel loads

Tyre type and size	Axle load [kN]	Tyre pressure [bar]	Contact area width [mm]	Contact area length [mm]	Average contact stress [bar]
Dual tyre 295/60R22.5	115	10.0	259	174	6.38
Dual tyre 315/80R22.5	90	6.5	255	185	4.77
Dual tyre 315/80R22.5	115	8.0	255	193	5.84
Wide single tyre 385/65R22.5	90	10.0	283	201	7.90
Wide single tyre 495/45R22.5	90	8.0	428	176	5.97
Wide single tyre 495/45R22.5	115	10.0	428	180	7.46

The transverse profiles of the permanent deformation in the asphaltic layers were calculated, as well as the transverse profiles of the horizontal strains at the bottom of the asphaltic layer, and the vertical strains at the top of the subbase.

These profiles were then input in TWINWHEELS. This spreadsheet first calculates transverse profiles of displacements, stresses and strains due to a dual tyre, by linear superposition of the profiles of the individual tyres. Then it calculates a transverse profile of a measure of damage by raising the strains to the n^{th} power. For asphalt strain (governing fatigue) the value n=5 was chosen, for the subbase strain (governing secondary rutting) the value n=4 was used. The transverse profile of the permanent deformation in the asphaltic layers does not need any conversion, as it already represents a distress profile.

TWINWHEELS then can calculate the effects of three factors, separately or in combinations.

- Lateral wander. This is simulated by linear superposition of many distress profiles, each shifted sideways according to a Laplace distribution of the wheel centres, with a lambda value of 0.12 m.
- Unequal load sharing of twinned tyres due to vehicle-intrinsic factors. This is based on the frequency distribution of load imbalance, as measured in NL (Nieuwsma 1999, see section 4.4.7 and Figure 4.23). For each step of 200 kgf load difference, new profiles of displacements, stresses and strains due to a dual tyre are calculated, by linear correction and superposition of the profiles of the individual tyres. These profiles are then converted to distress profiles as described above. These distress profiles are then linearly superimposed according to the measured frequency distribution.
- Unequal load sharing of twinned tyres due to a certain rutting in the pavement surface (only in combination with lateral wander). Depending on the transverse position of the dual wheel, the difference in vertical tyre compression due to the presence of a rut is calculated, using a commonly measured rut profile with a user-adjustable depth and a load difference of 0.5 kN for every mm in height difference (Penant 1999). (This value of 0.5 kN/mm corresponds well with the information from Zahnmesser (1981) cited in section 4.6.2.) The resulting load differences are then treated as in the previous paragraph.

The pavement wear factors for load imbalance due to 5 mm deep rutting were determined by dividing the maximum damage with load imbalance by the maximum damage without load imbalance. The rut depth of 5 mm was based on automated rut depth surveys on

2544 km (divided over 1998 and 1999) of the secondary road network in the Netherlands, giving an average depth of 5.2 mm (under a 1.2 m straightedge) in the right wheel track. The pavement wear factors are listed in Table 4.31. A factor of 0.90 means that a certain amount of passages of this tyre configuration in the presence of 5 mm rutting produces 90% as much damage at the most distressed point as the same amount of passages of this tyre configuration on an unrutted surface. The lower the factor, the more beneficial the effect of the rutting presence. The table shows that rutting, already present in the pavement, has a beneficial effect for the total damage, caused by dual tyres. This is caused by the fact that the wheel farthest from the rut centre (and hence 'highest' on the rut slope) takes a higher share of the total wheel load. In this way, a small portion of the load is transferred away from the most heavily loaded area in the rut centre. The beneficial effect is highest (4 to 5 %) for asphalt fatigue, and lowest (1%) for primary rutting.

Table 4.50 - Pavement wear factors for load imbalance due to 5 mm deep rutting

Tyre size	Factor for initial rutting based on		
	rut depth	longitudinal asphalt strain	subgrade strain
295/60R22.5 115 kN axle	0.99	0.96	0.98
315/80R22.5 90 kN axle	0.99	0.95	0.98
315/80R22.5 115 kN axle	0.99	0.96	0.98

The pavement wear factors for vehicle-intrinsic load imbalance were only calculated for the 315/80R22.5 tyre, at 115 kN axle load. The results are listed in Table 4.51.

Table 4.51 - Pavement wear factors for vehicle-intrinsic load imbalance

Tyre size	Factor for vehicle-intrinsic load imbalance based on		
	rut depth	longitudinal asphalt strain	subgrade strain
315/80R22.5 115 kN axle	1.02	1.00	1.00

4.6.7 Generalised effect of unequal load sharing on relative pavement wear

Based on the information in the previous sections, TG3 adopted the pavement wear factors for load imbalance, as listed in Table 4.52. The values for medium pavements are taken from section 4.6.6. These values were chosen as they are based on the distribution of load imbalance, as it was actually measured. The values for thick pavements were based on the findings from sections 4.6.3 and 4.6.4, that the influence of load imbalance was very small for thick pavements. Therefore, these factors were interpolated between 1 and those for medium pavements. The factors for thin pavements were similarly extrapolated. (For thin pavements, no factor is given for primary rutting, as this distress type is not considered to be relevant for these pavements.)

Table 4.52 - Factors for translation of pavement wear for dual tyres (relative to wide base singles) for load imbalance

		Primary rutting		Secondary rutting			Fatigue		
research question	aspect in consideration	medium	thick	thin	medium	thick	thin	medium	thick
8	load imbalance due to difference in inflation pressure and / or diameter	1.02[1]	1.02[2]	1.00[2]	1.00[1]	1.00[2]	1.00[2]	1.00[1]	1.00[2]
11	load imbalance due to transverse unevenness	0.99[1]	0.99[2]	0.97[2]	0.98[1]	0.99[2]	0.94[2]	0.96[1]	0.98[2]
	combined load imbalance	1.01	1.01	0.97	0.98	0.99	0.94	0.96	0.98

[1] Calculated value

[2] Inter- / extrapolated value

4.7 EFFECTS OF DYNAMICS

4.7.1 Introduction

When a vehicle is moving along a road, unevenness of the road will cause the vehicle to move up and down. This will cause a dynamic variation of the loads on the pavement, above and below their static values. The magnitude of this dynamic variation depends on the characteristics of the vehicle, the road surface's longitudinal profile and the speed of the vehicle. The variation generally increases with both speed and road unevenness, and may be ±15 (or more) percent even on a good road.

Dynamic loading increases pavement wear. Because of the power-law dependency of pavement distress on axle loads (see section 4.3.6.2), the loads above the static load increase the pavement wear more than the decrease in wear due to the loads below the static load. As stated before, the tyre characteristics (vertical spring compliance and damping) influence the dynamic vehicle loads. Wide-base single tyres generally have a lower vertical stiffness than dual tyre assemblies with the same load capacity.

The importance of dynamic loading was realised only relatively late and there has been little research in this area. An OECD expert group made a state-of the-art report (OECD 1992), and later OECD organised the DIVINE research project (OECD 1997).

As a part of the work of Task Group 3 of COST 334, the Technical Research Centre of Finland (VTT) measured dynamic properties of wide single tyres and dual tyres at the Virttaa test road and at a shaker table, using an instrumented vehicle. This study aimed to quantify the differences in pavement wear under moving dynamic wheel loads, between dual and wide base single tyres. Section 4.7.2 presents some basics of dynamic loading, section 4.7.3 describes the Finnish study, and section 4.7.4 presents the consequences of the Finnish results for the relative pavement wear of dual and wide base single tyres.

4.7.2 Basics of dynamic loading

The main movements of a vehicle are (Figure 4.63):

- body bounce, which means pitching and bouncing of the vehicle body. The natural frequency of this movement is usually about 1 to 3 Hz, where the lower limit corresponds to a modern suspension in good condition, and the upper limit represents a poor old-stylish suspension.
- axle hop, the vertical movement of the unsprung axle mass. The natural frequency is usually around 10 Hz.

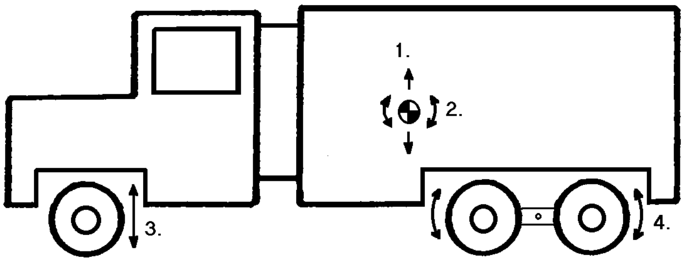


Figure 4.63 - Dynamic movements of vehicle, body bounce (1), body pitch (2) and axle hop (3) and tandem pitch (4).

There are other vehicle movements too, but these are of lesser importance and are not treated here.

The magnitude of dynamic loads is mostly expressed as the Dynamic Load Coefficient (DLC), as defined by the OECD as the ratio of the RMS (root mean square) dynamic wheel load to the mean wheel load. The RMS of the dynamic wheel load is essentially the standard deviation of the probability distribution of the total wheel load. The mean value reflects the static wheel load. So, the DLC is the coefficient of variation of the total wheel load. This is reported to range between 5 to10% for well-damped air suspensions and soft, well-damped steel leaf suspensions, and between 20 to 40% for less road-friendly suspensions (OECD 1992).

It is known that the dynamic properties of wide base single tyres and dual tyres are different. That is due to:

- the difference in weight (tyres and rims) and
- the structure and properties of the tyre.

As the effects of wide base single and dual tyres are assessed also the dynamic effects of tyres should be taken into account; they may have different “road-friendliness” in this respect.

Dynamic effects of wide base and dual tyres can be compared by the following means.

- Measurement of real dynamic tyre forces in the vehicle. This means that a vehicle is instrumented so that the instantaneous dynamic wheel load can be measured as the vehicle runs on the road.
- Measurement of dynamic tyre forces in an instrumented vehicle, when the vehicle wheels are excited by a shaker table (simulation of a road profile). On many shaker tables, no body pitch is excited.
- Measurement of strain and/or stresses in the pavement due to different tyres as the vehicle passes the test pavement (response measurements). These are compared to the measured dynamic axle loads. Because the test sections are usually very smooth, an artificial unevenness (bump) is needed to excite dynamic loads. Two bumps should be used, one to excite the body bounce etc and another for axle hop etc.
- Measurement of performance of a pavement under the effect of different tyres. This means road tests or tests in accelerated pavement test facilities, applying so many loadings of different tyres that the pavement fails.
- Modelling.

4.7.3 Finnish full scale testing

4.7.3.1 Introduction

Within the framework of COST 334, the Technical Research Centre of Finland (VTT) measured dynamic properties of wide single tyres and dual tyres, as part of the Finnish contribution to COST 334 (Huhtala et al. 2000a). The test programme consisted of four main parts, as follows.

1. Installation and calibration of instruments in the test vehicle.
2. Measurements of dynamic wheel loads at the shaker table of the Helsinki University of Technology.

3. Measurements of dynamic wheel loads and stresses and strains in the pavement at VTT's Virttaa test site, using bumps to excite the moving vehicle.
4. Measurements of dynamic wheel loads and stresses and strains in the pavement at the Virttaa test site, using the even road without any bumps.

4.7.3.2 Instrumented vehicle and tyres

The instrumented vehicle used in this study was hired by VTT and instrumented by the Helsinki University of Technology. It is a common three-axle trailer towed by a two-axle VOLVO FH12 tractor (Figure 4.48). The drive axle of the tractor and the middle axle of the tri-axle in the trailer were instrumented for measurements.

The tractor has tapered leaf springs on the front axle. The drive axle has four-bag air suspension. Both axles have anti-roll bar and they are damped with shock absorbers. For the test 315/70R22.5 dual tyres and 495/45R22.5 wide base single tyres (prototype) were used on the drive axle. 315/70R22.5 single tyres were used on the front axle. Appropriate tyre tread for the front and drive axle was selected by the test tyre provider Michelin.

The trailer is a common forty feet container carrier. The trailer axles together establish a tri-axle, but the first and third axle were lifted during the tests. Each axle has independent two-bag air suspension and is damped with shock absorbers. It was intended to compare 11R22.5 dual tyres with a 385/65R22.5 wide base single tyre, but the axle hub proved to be incompatible with the dual tyres. Therefore all tests were carried out with 385/65R22.5 XZA1 tyres on the trailer at 90 kN and 900 kPa. No measurements of this axle are shown, however.

The measurements shown here were made under the tractor drive axle at an axle load of 115 kN. The tyres used were a dual 315/70R22.5 XDA at 750 kPa and a wide base single 495/45R22.5 Energy XDA (prototype) at 900 kPa. These tyre pressures follow the manufacturer's recommendation for the applied load. All tyres were supplied by Michelin. Tests were executed at vehicle speeds of 45 and 80 km/h.

All measurements were carried out with the same payload. Nominal maximum axle loads were set placing concrete blocks inside the trailer and moving the fifth wheel of the vehicle to optimal position. Wheel loads and corresponding axle loads of the instrumented vehicle are presented in Table 4.53. Differences between left and right wheels are due to inclination of the road and perhaps unequal placing of the payload. Difference between the wide base single tyre and the dual tyre is due to different weight of the tyre assembly.

Table 4.53 - Wheel loads of the instrumented vehicle.

	Left wheel load [kgf]	Right wheel load [kgf]	Axle load [kgf]
Front axle (315/70R22.5)	3020	3200	6220
Drive axle (315/70R22.5)	5750	6010	11760
Drive axle (495/45R22.5)	5680	5940	11620
Trailer axle (385/65R22.5)	4630	4700	9330

The test vehicle was instrumented with strain gauges and accelerometers. Ideally, these are fitted on the axle housing, as shown in Figure 4.64. This was implemented on the drive axle. Due to lack of space on the trailer axle, the longitudinal support arm of the axle was used as a base for gauges, in stead of the axle itself. The methods for measuring dynamic wheel loads are described by LeBlanc et al (1992).

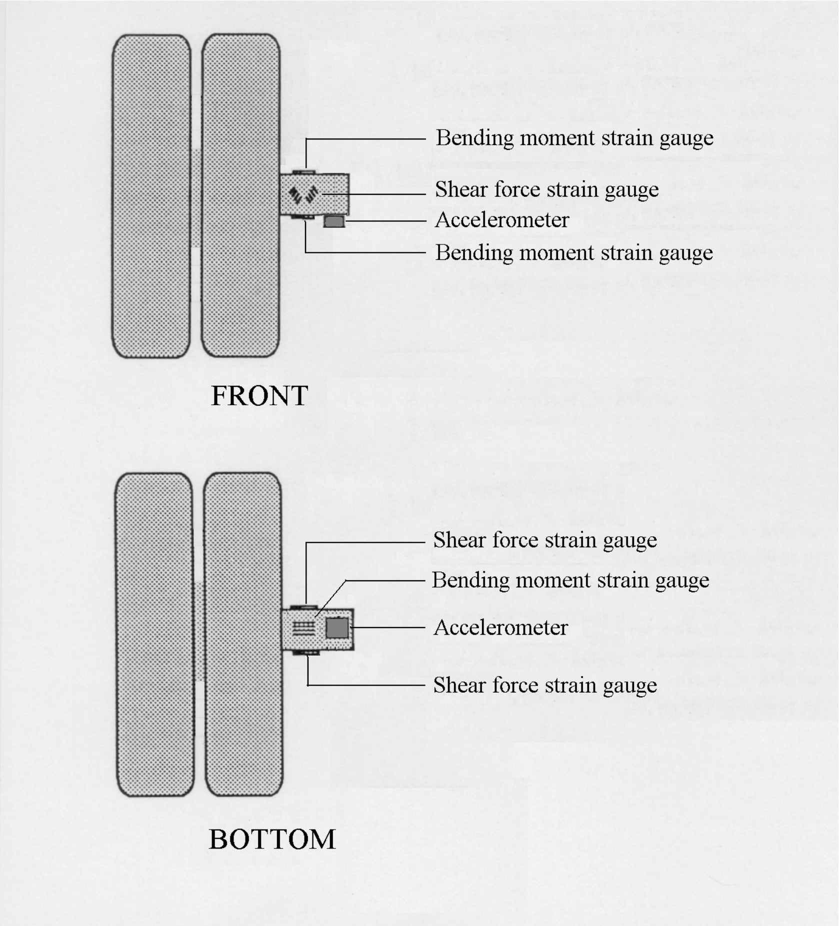


Figure 4.64 - The locations of the sensors on the axle of vehicle.

The test vehicle instrumentation was extensively calibrated, using both static and dynamic calibration at the shaker table. The drive axle produced good results. Due to the non-optimal sensor positions at the trailer axle, however, the results of this axle showed hysteresis in static calibration and phase shift in dynamic calibration. Therefore, the results of this axle are less reliable. These are not used here, however.

4.7.3.3 Shaker table

The shaker table of the Helsinki University of Technology, Laboratory for Mechanics of Materials is a servo-hydraulic loading machine. It has two actuators (Figure 4.65) and meets specifications as follows:

- Independent control system for both actuators
- Signal generator or external source can be used for the control
- Force capacity per actuator (static/dynamic) 250/180 kN
- Actuator stroke 150 mm
- Loading frequency up to 20 Hz (depending on the displacement and force level)
- Accelerometer, displacement sensor and load cell

Figure 4.65 - Truck tyre on the shaker table actuator.

The shaker table was used in order to excite dynamic movements of the instrumented vehicle, one axle at a time. For the dynamic wheel load calibration and the DLC (Dynamic Load Coefficient) calculation, three real longitudinal road profiles measured by the Finnish Road Surface Monitoring Vehicle were used as input. Each profile consists of five hundred metres data of vertical road displacements at 0.23 metre spacing. The profiles, having average IRI values of 1.6, 3.3 and 5.4 respectively, represent three road comfort classes, namely a fair, poor and bad road.

4.7.3.4 Virttaa test site

The Virttaa test site of VTT is located about 200 kilometres Northwest from Helsinki on National Highway 41. It is a highway section, widened to 40 m for use as a jet fighter airstrip. The instrumented test pavements are located in the shoulder of the road, so they are loaded only during VTT experiments. For these tests, a section with 150 mm thickness of bituminous layers was used, constructed in 1987. Thicknesses and materials of the test section pavement are shown in Table 4.28. Seven strain gauges in line at the bottom of the bituminous layers and three pressure cells have been used for these measurements.

Table 4.54 - Pavement layers and sensors at the Virttaa test site.

Layer	Thickness [mm]	Material	Depth of sensors [mm]
Asphalt	150	AC80	150
Base	150	Crushed rock	300
Subbase	400	Gravel	500
Subgrade	> 20 m	Sand	800

The International Roughness Index (IRI) of the Virttaa test site ranges from 1.17 to 2.87 mm/m per 100 m section, indicating a fairly smooth pavement, with the test pavement being in a 100 m section with an IRI of 2.15 mm/m. Two haversine-shaped bumps were used to excite the test vehicle, one plywood 4.0 m long and 0.050 m high to excite body bounce, and one steel 0.30 m long and 0.025 m high to excite axle hop. These bumps were designed for 45 km/h and excited nearly clear body bounce and axle hop at that speed. At 80 km/h the vehicle was excited in both modes simultaneously, but in analysis these could be differentiated.

Figure 4.66 shows a typical response of the vehicle to the long bump, and also shows the repeatability of these measurements in four vehicle passes.

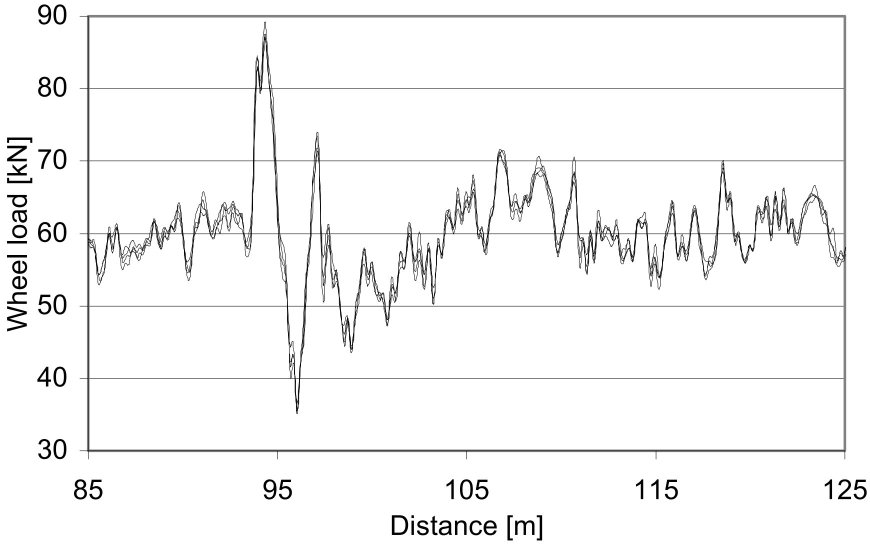


Figure 4.66 - Repeatability of dynamic loadings after the long bump, four vehicle passes

The bumps were positioned such that the maximum dynamic load was situated in the middle of the instrumented pavement section. To obtain better resolution with the given sensor spacing, the measurements were repeated with the bumps situated at several positions.

The dynamic wheel load measurements were matched to the pavement measurements by using an electric eye to detect reflective tapes glued across the road. Tapes were fixed every ten meters in order to ensure exact measurements.

4.7.3.5 Measurement results at the shaker table

DLCs (Dynamic Load Coefficient = standard deviation of dynamic load / mean value) were calculated for nine sets of measurements each on simulations of a fair, poor and bad road. The results of the DLC calculations can be seen in Figure 4.67. Each bar represents one repetition on a road profile. The wide base single tyre (495/45R22.5) produces systematically three to seven percent smaller values. The DLC values 0.095 – 0.099 on the simulated bad road clearly indicate that the test vehicle has first class suspension.

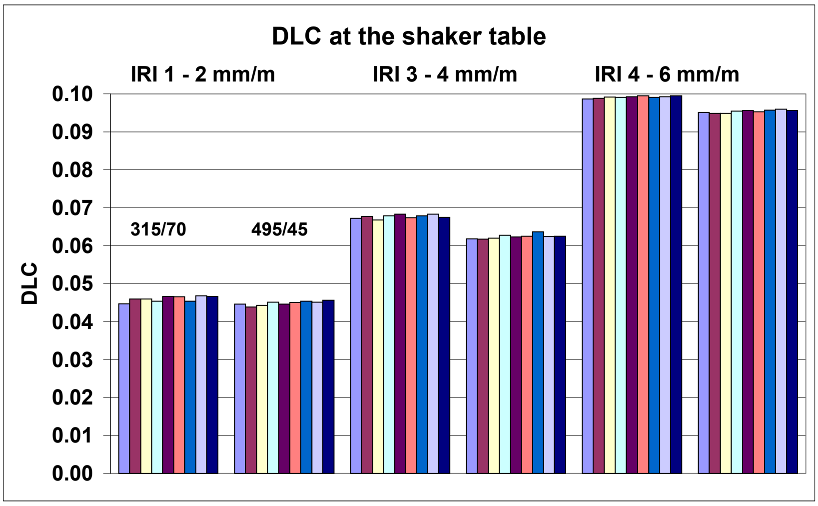


Figure 4.67 - Calculated DLC values for 315/70R22.5 and 495/45R22.5 tyres, shaker table simulations of fair, poor and bad road.

4.7.3.6 Measurements at the Virttaa test site without bump

Dynamic axle load measurements and simultaneous pavement response measurements were performed without bump in order to quantify the performance of the test tyres on even road. The results of the DLC calculations can be seen in Figure 4.68. Each bar represents one pass over the test section of about 200 metres length. The wide base single tyre (495/45R22.5) produces about 15 percent smaller values. A bigger deviation in results is due to the sensitivity of the tyre for sudden unevenness of the road. The lateral position of the vehicle was varied for each measurement.

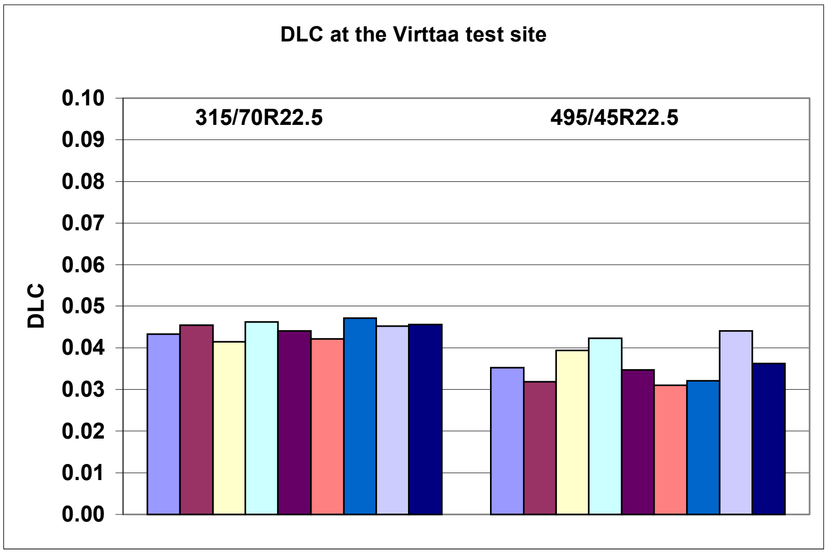


Figure 4.68 - Calculated DLC values for 315/70R22.5 and 495/45R22.5 tyres using different filters for measured signals, Virttaa test site without bump.

4.7.3.7 *Measurements at the Virttaa test site with bumps*

Figure 4.69 is an example of the measurement results using the short bump at a vehicle speed of 45 km/h. Similar results were found for the other bumps and vehicle speeds. The figure combines the measurements of the dynamic wheel loads and the strains at the bottom of the asphalt layer, showing the good correspondence of both these measurements. The figure combines data for three different locations of the bump relative to the pavement sensors. The plus mark (+) for 315/70R22.5 tyre in Figure 4.69 presents the estimated maximum value of the strain measurement after the short bump at 45 km/h.

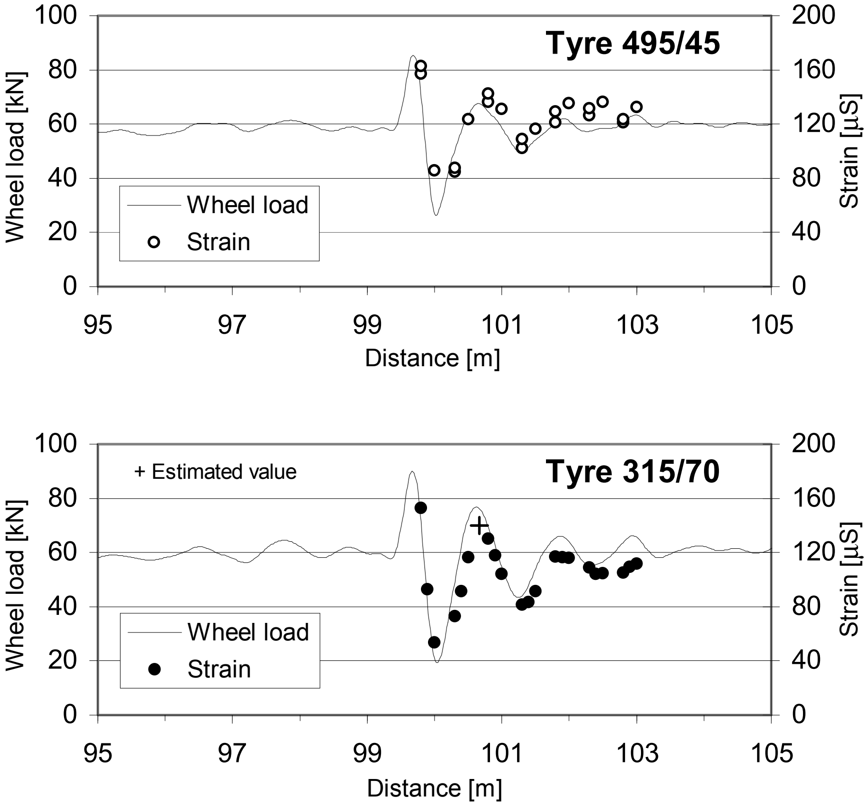


Figure 4.69 - Dynamic wheel loads and strains in the bottom of the asphalt layer after the short bump at 45 km/h.

All results are summarised in Table 4.55 and Table 4.56. Calculated strains at the nominal maximum axle load 115 kN are presented in Table 4.55. The wide base single tyre (495/45R22.5) produces 15 – 22 percent greater strains in the bottom of the asphalt layer.

Measured maximum strains after bumps and average strains on the even road (no bump) are presented in Table 4.56. Clear body bounce (sprung mass acting) and axle hop (unsprung mass acting) were excited especially at a speed of 45 km/h. However, so intense phenomena rarely can be seen on highways. The short bump caused 16 – 32% increase to strains in the bottom of the asphalt layer with the dual tyre (315/70R22.5) and 11 – 12% increase with the wide base single tyre (495/45R22.5). The long bump caused 12 – 19% increase to strains in the bottom of the asphalt layer with the dual tyre (315/70R22.5) and 3 – 18% increase with the wide base single tyre (495/45R22.5). At equal conditions, the measured strains in the bottom of the asphalt layer are 3 - 22% greater under the wide-base single tyre.

Table 4.55 - Calculated strains in the bottom of the asphalt layer at 57.5 kN wheel load (axle load 115 kN).

		315/70R22.5		495/45R22.5	
		Strain [µm/m]	Strain [%]	Strain [µm/m]	Strain [%]
Short bump	45 km/h	101.6	100	118.4	116.5
	80 km/h	97.8	100	119.5	122.2
Long bump	45 km/h	101.9	100	121.4	119.2
	80 km/h	99.7	100	114.1	114.5

Table 4.56 - Measured strains in the bottom of the asphalt layer, maxima after bumps and averages without bump.

		315/70R22.5		495/45R22.5	
		Strain [µm/m]	Strain [%]	Strain [µm/m]	Strain [%]
No bump	45 km/h	105.7	100	128.5	100
Short bump	45 km/h	140.0*	132.5	143.8	111.9
Long bump	45 km/h	125.8	119.0	151.2	117.7
No bump	80 km/h	96.4	100	113.1	100
Short bump	80 km/h	112.1	116.3	125.0**	110.5
Long bump	80 km/h	107.7	111.7	116.6	103.1

* Estimated value, see Figure 4.69

** Average of three points

4.7.3.8 Conversion of DLC differences to pavement wear differences

How can differences in dynamic load (variations) be translated to differences in pavement wear? In this respect, the concept of spatial repeatability is important. This is described extensively elsewhere, referred to by Huhtala et al. (2000a), and is summarised here.

When the same vehicle with the same load passes the same road several times at the same speed, the dynamic loadings will be the same at each point of the road, as shown in Figure 4.66. In this case there is a (near-)perfect spatial repeatability. Some points of the road are always loaded more heavily than others, and the most heavily loaded are the normative points for the pavement life determination (assuming constant pavement quality over the road length). Changes in dynamic load characteristics of the vehicle, e.g. due to change of tyres, are mainly relevant to the extent in which they influence the dynamic load at the normative points. A dynamic load increase of 10% will then result in a pavement wear increase of 46%, using the 4th power formula for the Load Equivalency Factor, detailed in section 4.3.6.2.

If there are several vehicles at several speeds, the extent of spatial repeatability varies depending on the unevenness of the road. As each vehicle at each speed responds differently to the road profile, it becomes less likely that the maximum dynamic axle loads all occur at the same position. After a single unevenness (bump) there may be a good spatial repeatability, as all vehicles will have high dynamic loads on the bump and a short distance thereafter. On an (almost) even road, however, no spatial repeatability can be detected. The dynamic loadings on a road caused by several vehicles with different speeds are not fully known. Translating these dynamic loads to pavement wear effects is therefore difficult.

If complete absence of spatial repeatability is assumed, the dynamic loads are randomly distributed on the road, and each spot will be subjected to the full spectrum of dynamic loads. Then the effect of changes in DLC could be calculated by calculating the total pavement wear effect of each probability distribution of the dynamic wheel loads (corresponding to each DLC, shown in Figure 4.70), and expressing these as a relative number.

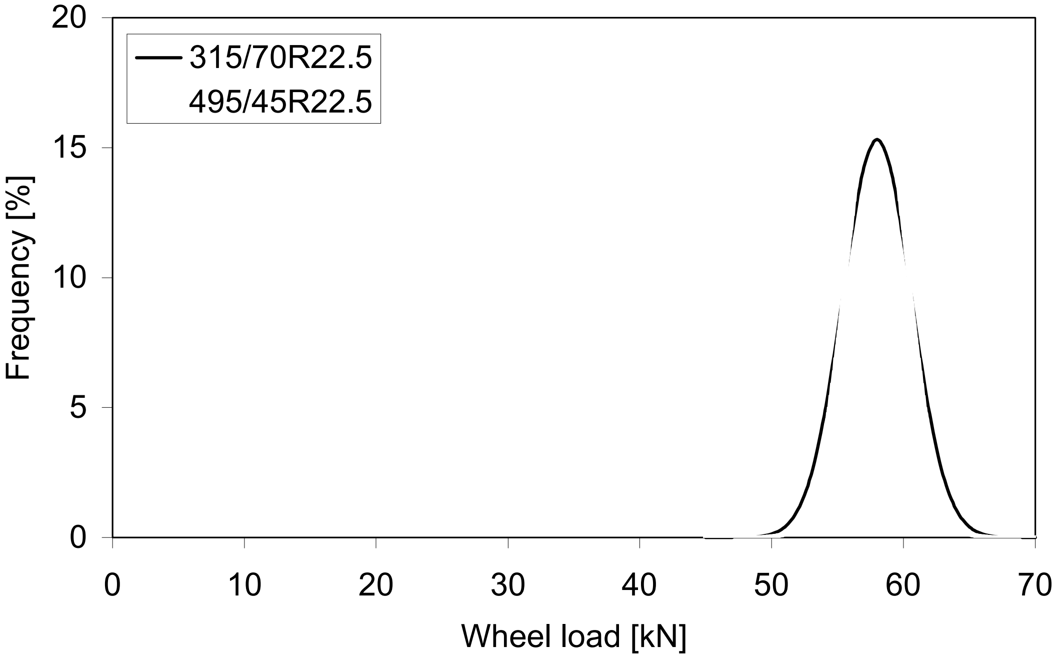


Figure 4.70 - Calculated wheel load distributions on even road at 80 km/h.

Eisenmann (1975) published a formula, quantifying road stress in a dynamic road factor (ν) as a function of DLC:

$\nu = 1 + 6s^2 + 3s^4$ (s = DLC).

This assumes that there is no spatial repeatability. Using this formula, the dynamic road factors were calculated for the measured DLC's at the shaker table and the Virttaa test site. These are shown in Table 4.57.

Table 4.57 - Calculated dynamic road factors (ν) for 315/70R22.5 and 495/45R22.5 tyres; shaker table simulations of fair, poor and bad road, and Virttaa site measurements.

Road	315/70R22.5		495/45R22.5	
	Factor	Factor [%]	Factor	Factor [%]
Fair road	1.012	100	1.012	99.9
Poor road	1.027	100	1.023	99.6
Bad road	1.059	100	1.054	99.6
Virttaa	1.012	100	1.009	99.7

The wide base single tyre (495/45R22.5) produces slightly better values than the dual tyre (315/70R22.5).

As implied above, the total absence of spatial repeatability is probably a somewhat unrealistic assumption, producing estimates for the pavement wear effects which are too low.

4.7.3.9 Conclusions of the Finnish experiment

Dynamic Load Coefficient (DLC) calculations from the shaker table data showed that the wide base single tyre 495/45R22.5 has 3 – 7 percent smaller or better values than 315/70R22.5 dual tyres.

Corresponding DLC calculations on the Virttaa test site measurements showed about 15 percent smaller or better values for the 495/45R22.5 tyre.

Using Eisenmann's formula, this translates to about 1% lesser pavement wear for the wide-base single tyre, due to dynamic effects alone. (The reduction in pavement wear for the wide-base single tyre is probably higher in reality, as Eisenmann's formula assumes the absence of spatial repeatability, whereas such repeatability does occur in practice.)

Note however, that this better performance in dynamics of the wide-base single tyre is more than offset by the larger strains it causes in the pavement (shown in section 4.5.7), due to its lesser width, higher inflation pressure and hence lesser load spreading. The resulting PWR values for the wide single tyre, relative to the dual tyre assembly, on the tested pavement (150 mm asphalt thickness) were 1.89 for fatigue and between 2.14 and 1.0 (decreasing with increasing depth in the pavement) for secondary rutting.

4.7.4 Generalised effect of tyre dynamics on relative pavement wear

The Finnish research, described in the previous section, only compared one wide single tyre and one dual tyre, and established the relative pavement wear effects on one test pavement only. Therefore, care should be taken in generalising the results to other tyre types and pavement thicknesses. Further research with different types of tyres, vehicles and pavements is recommended.

Further data were contributed by Volvo (Aurrell 1999) who tested 315/70R22.5 dual and 495/45R22.5 wide single tyres on the same rigid vehicle. The vehicle was tested on a road simulator (shaker table), simulating a medium bad road profile. The tyre forces for the wide single tyre were about 17% lower than for the dual tyre assembly. This is in close correspondence with the Finnish results. This does not widen the scope of available information very much, however, as the tested tyre types were the same as in the Finnish tests, as well as the vehicle manufacturer.

As no other data were available, TG3 decided to assume that the Finnish findings are representative for all wide-base single tyres and dual tyre assemblies. This means that a Pavement Wear Ratio of 0.99 is assumed for the dynamic effects of wide-base singles, relative to dual tyre assemblies, for all distress types on primary roads. For secondary roads, a PWR of 0.97 is assumed. These factors only cover the effects of differences in dynamic loading between these tyre types, and should be combined with the other factors in the Tyre Configuration Factor (such as footprint width) as quantified in section 4.5.10.

4.8 COMBINING THE RESULTS TO TYRE CONFIGURATION FACTORS (TCF)

4.8.1 Introduction

In section 4.5.10 the basic formulae have been derived for the relative pavement wear for different tyres sizes at equal loads. Distinguished are three different distress mechanisms and three thicknesses. Formulae for primary rutting were given only for medium and thick pavements, because for thin pavements this distress mechanism is considered not to be relevant for determining the end of pavement life.

These formulae, however, deal with ideal loading conditions, which means equal load distribution in case of dual tyre assemblies and a completely even road, both in longitudinal and in transversal direction. Sections 4.6 and 4.7 described the factors which have to be taken into account for translation from this ideal situation to real world conditions.

Combination of these elements, including the choice of a reference tyre, result in the final TCF formulae, which are described in section 4.8.2.

Section 4.8.3 gives a critical analysis of the TCF formulae as well as a quantitative answer on the formulated research questions:

3) What is the relative effect of wide base singles and dual assemblies for equal inflation pressures (or equal size of contact areas) and equal loads?
4) What is the relative effect of tyre inflation pressure of the current tyres or size of contact area at equal load for wide base singles and dual assemblies?
5) What is the effect on pavement wear of possible future lower or higher tyre inflation pressures at equal load for wide base singles and dual assemblies?
6) What is the relative effect of tyre diameter (or the shape of the contact area) for wide base singles and dual assemblies for equal inflation pressures (or equal size of contact areas) and equal loads?
9) What is the effect on pavement wear of under- and overinflation, at equal load, for wide base single tyres and dual tyre assemblies?

In section 4.8.4, the TCF values are calculated for the currently available and possible future tyres, to enable comparison of the tyres to each other. Section 4.8.5 finally presents an overview of the average TCF values of the common current and possible future tyres for the towed, the driven and the steering axle.

4.8.2 Completion of the TCF formulae

4.8.2.1 Total factor for translation from ideal to real world conditions

The following factors have to be taken into account:

- The generalised effect of load imbalance of dual tyres due to a possible difference in inflation pressure and / or difference in tyre diameter and bending of the axle (see section 4.6.7). Of course, the respective factors are equal to 1.00 for wide base single tyres.
- The difference in dynamic behaviour (see section 4.7), taking duals as a reference.

In the two tables below the individual factors are combined to total factors for the dual tyre assemblies and the wide base single tyres.

Table 4.58 - Total factors for translation of pavement wear from ideal conditions to real world conditions – dual tyre assemblies

		Primary rutting		Secondary rutting			Fatigue		
research question	aspect in consideration	medium	thick	thin	medium	thick	thin	medium	thick
8 and 11	generalised effect load imbalance	1.01	1.01	0.97	0.98	0.99	0.94	0.96	0.98
10	difference in dynamic behaviour	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
Total factor dual tyres		**1.01**	**1.01**	**0.97**	**0.98**	**0.99**	**0.94**	**0.96**	**0.98**

Table 4.59 - Total factors for translation of pavement wear from ideal conditions to real world conditions – wide base single tyres

		Primary rutting		Secondary rutting			Fatigue		
research question	aspect in consideration	medium	thick	thin	medium	thick	thin	medium	thick
8 and 11	generalised effect load imbalance	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
10	difference in dynamic behaviour	0.97	0.99	0.97	0.97	0.99	0.97	0.97	0.99
Total factor wide base single tyres		**0.97**	**0.99**	**0.97**	**0.97**	**0.99**	**0.97**	**0.97**	**0.99**

Comparison of these factors shows that there are only marginal differences between the respective factors for duals and wide base singles. It also can be seen that all factors are close to one, indicating that there are only small differences between the pavement wear under ideal or real world conditions.

Although not investigated, it is assumed that the dynamic behaviour of standard single tyres as mounted on the steering axles (such as from the 295 and the 315 series) is similar to the dynamic behaviour of these tyres in dual assemblies. Assuming this and given the fact that the factor for load imbalance of single tyres is equal to one, the total factor for translation to real world conditions will be equal to one for all cases.

4.8.2.1 Choice of the reference tyre

Before deriving the complete set of TCF's, the characteristics of a reference tyre need to be defined, to which the pavement wear of all tyres is referred. It must be stated that the choice of the reference tyre has no influence in a direct comparison of different tyres to each other, since the TCF is a relative model. This makes the choice rather arbitrary.

In current pavement design codes commonly a dual assembly is chosen for the reference tyre. The type however is seldom specified. TG3 decided to choose the 295/80R22.5 dual tyre as reference tyre, as this is currently one of the most common tyres, mounted especially on the driven axles.

Table 4.60 presents the chosen characteristics, assuming an axle load of 10 tonnes.

Table 4.60 - Characteristics of the reference tyre (295/80R22.5) with 10 tonnes axle load

Width	2*235 mm
Total width	570 mm
Diameter	1059 mm
Length	198 mm
Contact area	2*46500 mm^2
Pressure ratio	1.0 (means inflated as recommended)
Inflation pressure	750 kPa in operating conditions (650 kPa cold)

4.8.2.2 Combining all elements to the final set of TCF formulae

The above given factors for translation to real world conditions, the formulae derived in the regression analysis of section 4.5.10, and the choice for the reference tyre characteristics (Table 4.60) were combined. This results in the final set of TCF formulae, presented in Table 4.61.

Table 4.61 - Final set of TCF formulae

		Total factor for translation to real world conditions		
Pavement thickness	Formulae derived in regression analysis in section 4.5.10	Dual tyres	Wide base single tyres	Single tyre
Distress mode primary rutting				
Medium[1]	$(\text{width}/470^{-1.68} * (\text{length}/198)^{-0.85} * (\text{pres. ratio})^{0.81}$ or $(\text{width}/470)^{-1.65} * (\text{pres. ratio})^{1.42} * (\text{diameter}/1059)^{-1.12}$	1.01	0.97	1.00
Thick	$(\text{width}/470)^{-1.68} * (\text{length}/198)^{-0.85} * (\text{pres. ratio})^{0.81}$ or $(\text{width}/470)^{-1.65} * (\text{pres. ratio})^{1.42} * (\text{diameter}/1059)^{-1.12}$	1.01	0.99	1.00
Distress mode secondary rutting				
Thin	$(\text{total width}/570)^{-2.57} * (\text{pres. ratio})^{1.58}$	0.97	0.97	1.00
Medium[2]	$(\text{total width}/570)^{-2.57} * (\text{pres. ratio})^{1.58}$	0.98	0.97	1.00
Thick	about equal to 1			
Distress mode fatigue				
Thin	$(\text{total width}/570)^{-2.88} * (\text{length}/198)^{-3.13}$ or $(\text{total width}/570)^{-2.44} * (\text{diameter}/1059)^{-2.47}$	0.94	0.97	1.00
Medium	$(\text{total width}/570)^{-1.36} * (\text{length}/198)^{-1.40}$ or $(\text{total width}/570)^{-1.23} * (\text{diameter}/1059)^{-1.14}$	0.96	0.97	1.00
Thick	about equal to 1			

[1] Hardly any data were available for primary rutting in medium pavements, so these were combined with thick pavements. TG3 expects the pavement wear effects for primary rutting in medium pavements to be similar to those in thick pavements.

[2] Available data did not allow a distinction between thin and medium pavements. However, TG3 expects the pavement wear effects for secondary rutting in medium pavements to be smaller than in thin pavements, similar as for fatigue.

4.8.3 Evaluation and sensitivity analysis of the TCF formulae

The above mentioned formulae can be used to find an answer to the research questions 3 to 6 and 9, as mentioned in section 4.8.1. For that purpose some calculations were made using the TCF formulae and arbitrarily chosen variations of the input parameters. The results are summarised in Table 4.62.

Table 4.62 - Quantification of effects, based on the TCF formulae

Question	Description	Primary rutting		Secondary rutting			Fatigue		
	pavement thickness:	med.[2]	thick[2]	thin[3]	med.[3]	thick	thin	med.	thick
3	wide-base versus dual (equal contact area, contact width of 500 mm, divided in 2*250 mm with 100 mm spacing in the case of the dual assembly)	-4%	-2%	58%	58%	negligible	61%	26%	negligible
	wide-base versus dual (equal total contact area, contact width of 400 mm, divided in 2*200 mm with 100 mm spacing in the case of the dual assembly)	-4%	-2%	76%	76%	negligible	78%	33%	negligible
4	11% increase av. contact stress by 10% decrease in length[1] keeping width constant	9%[1]	9%[1]	unknown	unknown	negligible	39%[1]	16%[1]	negligible
	dual: 11% increase av. contact stress, by 10% decrease in width, keeping length constant	19%	19%	25%	25%	negligible	23%	11%	negligible
	wide base: 11% increase av. contact stress, by 10% decrease in width, keeping length constant	19%	19%	31%	31%	negligible	29%	14%	negligible
5	25% increase av. contact stress by 20% decrease in length[1], keeping width constant	21%[1]	21%[1]	unknown	unknown	negligible	101%[1]	37%[1]	negligible
	dual: 25% increase av. contact stress by 20% decrease in width, keeping length constant	45%	45%	59%	59%	negligible	56%	25%	negligible
	wide base: 25% increase av. contact stress by 20% decrease in width, keeping length[1] constant	45%[1]	45%[1]	77%[1]	77%[1]	negligible	72%[1]	32%[1]	negligible
6	10% decrease in diameter (dual and wide base)	13%	13%	unknown	unknown	negligible	30%	13%	negligible
	10% decrease in length[1], keeping width constant, so 10% increase in average contact stress	9%[1]	9%[1]	unknown	unknown	negligible	39%[1]	16%[1]	negligible
9	10% lower inflation pressure than recommended	-14%	-14%	-15%	-15%	negligible	unknown	unknown	negligible
	10% higher inflation pressure than recommended	14%	14%	16%	16%	negligible	unknown	unknown	negligible

[1] These effects are calculated using the TCF formulae containing the contact area length, all other effects are based on the TCF formulae containing the tyre diameter.

[2] The TCF formulae for primary rutting are based mainly on data for thick pavements, including only one medium pavement

[3] Although TG3 expects the effects on secondary rutting for thin pavements to be stronger than for medium pavements, the limited available data did not allow a distinction in TCF formula between thin and medium pavements.

Unless stated differently, the values are based on calculations with the formulae containing the tyre diameter (in stead of the contact length). The advantage of these models is the fact that no information on contact area is necessary, which data is more difficult to gather.

Assuming equal loading, the following conclusions can be drawn.

<u>primary rutting</u>

- For equal contact area, the pavement wear of wide base singles and dual tyres is almost equal, with a slight benefit for wide base singles.
- The width of the contact area between the pavement and the tyre (or the two tyres together) is the most important parameter. The greater the width, the lower the pavement wear.
- The size of the contact area, or vice versa the average contact stress, is important too. The greater the contact area or the lower the contact stress, the lower the pavement wear will be.
- A decrease in tyre diameter, keeping the contact width constant, results in higher pavement wear. This can be explained by the fact that decreasing the diameter at constant width implies decreasing contact area, so increasing contact stress.
- Underinflated tyres (low value of pressure ratio) have lower pavement wear, whereas overinflated tyres have higher pavement wear.

<u>secondary rutting</u>

- Available data did not allow a distinction between thin and medium pavements. However, it can be expected that the pavement wear effects for secondary rutting in medium pavements are smaller than in thin pavements, similar as for fatigue.
- The total contact width (for dual tyres equal to two times the width of the tyre - pavement contact area plus 100 mm in between) is the most important parameter.
- As a consequence, comparing wide base singles with dual tyres, keeping all parameters constant (equal width, length, diameter and pressure ratio), wide base singles have higher pavement wear. The explanation is simple, as secondary rutting deals with stress conditions at greater depth in the pavement than primary rutting. Due to the principle of Saint Venant, the dual therefore acts more or less as a single tyre with a 100 mm greater width.
- Increasing width (and total width) results in lower pavement wear, both for dual tyres and wide base singles.
- Size of the contact area or the average contact stress also is important. The greater the contact area or vice versa the lower the contact stress, the lower the pavement wear will be.
- The influence of tyre diameter is unknown. It can be expected that the influence will be more or less the same as for fatigue.
- Underinflated tyres (low value of pressure ratio) have lower pavement wear, whereas overinflated tyres have higher pavement wear.

fatigue

- The total contact width (for dual tyres equal to two times the width of the tyre - pavement contact area plus 100 mm in between) is the most important parameter.
- As a consequence, comparing wide base singles with dual tyres, keeping all parameters constant (equal width, length, diameter and pressure ratio), wide base singles have higher pavement wear. The explanation is simple, fatigue deals with stress conditions at greater depth in the pavement than primary rutting. Due to the principle of Saint Venant, the dual therefore acts with respect to fatigue more or less as a single tyre with a 100 mm greater width.
- Increasing width (and total width) results in lower pavement wear, both for dual tyres and wide base singles.
- Size of the contact area or the average contact stress is important too. The greater the contact area or vice versa the lower the contact stress, the lower the pavement wear will be.
- A decrease in tyre diameter at constant contact width results in higher pavement wear. This can be explained by the fact that decreasing the diameter at constant contact width implies decreasing contact area, so increasing contact stress.
- The influence of underinflation or overinflation is unknown. It can be expected that there will be a similar sensitivity as found for secondary rutting.

4.8.4 Tables of TCF values for the currently available and possible future tyres.

TCF values were calculated for the currently available and possible future commercial tyres, using the formulae for the primary and secondary roads based on tyre width and diameter as given in the previous section. In the calculations it was assumed that the tyres are inflated as recommended by the manufacturer. By using the formulae containing the tyre diameter in stead of the contact area length, the TCF value is independent of the axle load. Note that the reference tyre is considered under ideal conditions (equal load sharing, even pavement surface), whereas the same 295/80R22.5 tyre lower in the table is considered under ‘real world’ conditions.

For the secondary roads (medium pavements) the TCF values for the individual distress modes are given, as well as some kind of average value. This is based upon a weighing factor of 20%, 40% and 40% for the primary rutting, secondary rutting and fatigue distress modes respectively. These same factors have been used in the work of TG 6.

Table 4.63 - TCF values for towed axles

						Tyre Configuration Factor				
						Primary roads	Secondary roads			
		tyre width	cont. area width	total width	dia-meter	primary rutting	weigh-ted average	primary rutting	secon-dary rutting	fatigue
Tyre size	Fitment	mm	mm	mm	mm					
Ref. tyre	single	235	470	570	1059	1.00	1.00	1.00	1.00	1.00
205/65R17.5	dual	175	350	450	711	**2.57**	**2.04**	**2.57**	**1.80**	**2.02**
215/75R17.5	dual	175	350	450	767	**2.36**	**1.93**	**2.36**	**1.80**	**1.85**
245/70R17.5	dual	215	430	530	789	**1.63**	**1.39**	**1.63**	**1.18**	**1.47**
245/70R19.5	dual	200	400	500	839	**1.71**	**1.48**	**1.71**	**1.37**	**1.47**
265/70R19.5	dual	210	420	520	872	**1.51**	**1.34**	**1.51**	**1.24**	**1.34**
10.00R20 [1]	dual	184	368	468	1054	**1.52**	**1.45**	**1.52**	**1.63**	**1.23**
10R22.5	dual	186	372	472	1017	**1.56**	**1.46**	**1.56**	**1.59**	**1.27**
11R22.5	dual	184	368	468	1054	**1.52**	**1.45**	**1.52**	**1.63**	**1.23**
315/80R22.5	dual	247	494	594	1085	**0.91**	**0.89**	**0.91**	**0.88**	**0.89**
385/55R22.5	single	329	329	329	998	**1.91**	**2.78**	**1.87**	**3.98**	**2.04**
385/65R22.5	single	285	285	285	1071	**2.23**	**3.64**	**2.19**	**5.76**	**2.25**
425/65R22.5	single	308	308	308	1126	**1.86**	**3.02**	**1.82**	**4.72**	**1.93**
445/45R19.5	single	380	380	380	895	**1.70**	**2.21**	**1.66**	**2.75**	**1.93**
445/65R22.5	single	340	340	340	1155	**1.53**	**2.43**	**1.50**	**3.66**	**1.66**

[1] Used frequently in the past, now almost obsolete

Table 4.63 shows the TCF values for tyres on towed axles. It shows there can be a lot of difference in TCF value within the range of currently available and possible future dual tyres as well as within the range of wide base singles

For example the 17.5 inch dual tyres have TCF values on primary roads ranging from 1.63 to 2.57. The TCF values for the 19.5 and 22.5 inch dual tyres on primary roads are considerably lower, ranging from 0.91 to 1.71. Ignoring the 315/80R22.5 tyre which is not much used on towed axles, the TCF range is from 1.51 to 1.71. For the wide base singles (all 19.5 or 22.5) the TCF value on primary roads ranges from 1.53 to 2.23.

For secondary roads the TCF values of the duals are marginally lower than the respective values for primary roads, whereas for the wide base singles the TCF values on secondary roads are 30% to 60% higher than on primary roads.The main reason for this is the fact that on secondary roads the total width value is of importance. For duals this includes the width between the two tyres of the assembly (about 100 mm).

There is a range in TCF values among the dual tyres for driven axles too, as shown in Table 4.63. For example the TCF value on primary roads for duals varies from about 0.91 for the 315/80R22.5 tyre to 1.52 for the 11R22.5 tyre. This latter type however is seldom used nowadays on driven axles. The tyre with the next highest TCF value is the 12R22.5 (TCF of 1.27). In the past this was a very popular tyre on driven axles, just as the 11.00R20 tyre (TCF of 1.21).

Like for the towed axles, the TCF values for the duals on the drive axle on secondary roads are marginally lower than the respective values on primary roads.

On primary roads the TCF value (1.22) of the prototype extra-wide base single tyre 495/45R22.5, for use on drive axle, is just in the range of the respective values of the currently available duals.

On secondary roads the TCF value of this prototype extra-wide base tyre (1.64) is 13% higher than the TCF of the most damaging dual assembly, the 11R22.5. It is 33% and 39% higher than the previously popular 12R22.5 and the 11.00R20 dual assembly respectively.

Table 4.64 - TCF values for driven axles

						Tyre Configuration Factor				
						Primary roads	Secondary roads			
		tyre width	cont. area width	total width	dia-meter	primary rutting	weigh-ted average	primary rutting	secon-dary rutting	fatigue
Tyre size	Fitment	mm	mm	mm	mm					
Ref. tyre	single	235	470	570	1059	1.00	1.00	1.00	1.00	1.00
11.00R20 [1]	dual	207	414	514	1086	**1.21**	**1.18**	**1.21**	**1.28**	**1.06**
295/60R22.5	dual	244	488	588	924	**1.11**	**1.02**	**1.11**	**0.90**	**1.08**
295/80R22.5	dual	235	470	570	1059	**1.01**	**0.98**	**1.01**	**0.98**	**0.96**
315/70R22.5	dual	253	506	606	1024	**0.93**	**0.89**	**0.93**	**0.84**	**0.93**
315/80R22.5	dual	247	494	594	1085	**0.91**	**0.89**	**0.91**	**0.88**	**0.89**
11R22.5	dual	184	368	468	1054	**1.52**	**1.45**	**1.52**	**1.63**	**1.23**
12R22.5	dual	201	402	502	1085	**1.27**	**1.23**	**1.27**	**1.36**	**1.09**
495/45R22.5 [2]	single	427	427	427	1013	**1.22**	**1.64**	**1.19**	**2.04**	**1.46**

[1] Used frequently in the past, now almost obsolete

[2] Prototype tyre

The values in Table 4.65 show the TCF values for single and wide base single tyres on the steering axle. In average the current standard single tyres have high TCF values of about 3 to 4 on primary roads and about 5 to 8 on secondary roads. This means that for the same axle load, they are about three to four and five to eight times as agressive as the reference tyre. This can be understood by the fact that the reference tyre in the TCF formulae is a dual assembly. For the steering axle this is in fact not a fair comparison.

Nevertheless it indicates that tyres on steering axles can cause considerable pavement wear, compared with driven and towed axles. For a proper comparison, the difference in load level should be considered too. Even then, it stands to reason that a steering axle load of 7 tonnes on two single tyres can be more detrimental than a driven axle load of 11.5 tonnes on two dual tyre assemblies.

The wide base single tyres on the steering axle show the same TCF values as on the driven and towed axle, which are much lower than the respective values from the standard single tyres. The main reason of this is the much greater width of wide base singles in comparison with the standard single tyres.

Table 4.65 - TCF values for steering axles

						Tyre Configuration Factor				
						Primary roads	Secondary roads			
		tyre width	cont. area width	total width	dia-meter	primary rutting	weigh-ted average	primary rutting	secon-dary rutting	fatigue
Tyre size	Fitment	mm	mm		mm					
Ref. tyre	dual	235	470	570	1059	1.00	1.00	1.00	1.00	1.00
11.00R20[1]	single	207	207	207	1086	**3.76**	**7.51**	**3.76**	**13.51**	**3.38**
12R22.5	single	201	201	201	1085	**3.95**	**8.02**	**3.95**	**14.57**	**3.51**
295/60R22.5	single	244	244	244	924	**3.44**	**5.55**	**3.44**	**8.85**	**3.32**
295/80R22.5	single	235	235	235	1059	**3.14**	**5.72**	**3.14**	**9.75**	**2.97**
315/70R22.5	single	253	253	253	1024	**2.89**	**4.93**	**2.89**	**8.06**	**2.82**
315/80R22.5	single	247	247	247	1085	**2.81**	**5.08**	**2.81**	**8.58**	**2.72**
385/55R22.5	single	329	329	329	998	**1.91**	**2.78**	**1.87**	**3.98**	**2.04**
385/65R22.5	single	285	285	285	1071	**2.23**	**3.64**	**2.19**	**5.76**	**2.25**

[1] Used frequently in the past, now almost obsolete

4.8.5 Overview of average TCF values of the common current and possible future tyres

Table 4.66 summarizes per axle type the average values of the contact area width, the tyre diameter and the according TCF values for the common current and possible future tyres (with 19.5 and 22.5 inch rim).

The calculation of the average values is based on the range of tyres as used in the previous tables, with the exception of the following tyres:

- the obsolete tyres which have been marked with a footnote in the previous tables,
- the 11R22.5 dual tyre for use on driven axle, because of the very low share (lower than 5%) of this tyre (see Glaeser 1998 and Nieuwsma 1999), in combination with the large difference in TCF value with the more popular ones.
- the 315/80 dual tyre for use on towed axle because of a very low share of this tyre in combination with the large difference in TCF value with the more popular ones.

Table 4.66 - Overview of average values of width of contact area, diameter and TCF value for the observed range of common current and possible future tyres for the different axles (rim size 19.5 and 22.5)

				Primary roads		Secondary roads	
Axle	Fitment	Contact area width	Dia-meter	TCF	Wide base versus dual or single	TCF	Wide base versus dual or single
		mm	mm				
Towed	Dual	410	973	1.57		1.43	
	Wide base single	328	1049	1.84	+17%	2.82	+97%
Driven	Dual	455	1038	1.04		1.00	
	Wide base single	427	1013	1.22	+17%	1.64	+64%
Steering	Single	245	1023	3.25		5.86	
	Wide base single	307	1035	2.07	-36%	3.21	-45%

Figure 4.71 to Figure 4.73 present a graphical overview of the TCF values of the individual tyres, as listed in Table 4.63 to Table 4.65. Dual tyres are represented in green, ‘standard’ single tyres in red and wide base single tyres in blue. The TCF values for primary roads are represented by solid bars, the TCF values for secondary roads are striped.

The values in the table as well as the graphs show that there is not one unique answer to the question whether the common current and (possible) future wide base singles are better or worse with respect to pavement damage.

Replacement of duals by wide base singles, both on towed or driven axles, generally results in more pavement damage, for the observed range of common current and possible future tyres. This effect is more pronounced on secondary roads.

Replacement of single tyres on steering axles by wide base singles, however, results in a reduction of pavement damage.

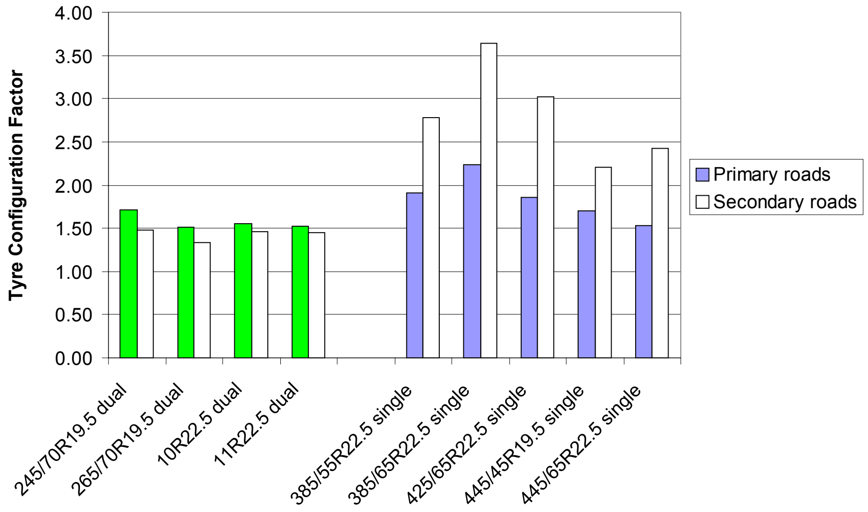


Figure 4.71 - TCF of common current and possible future tyres for towed axles

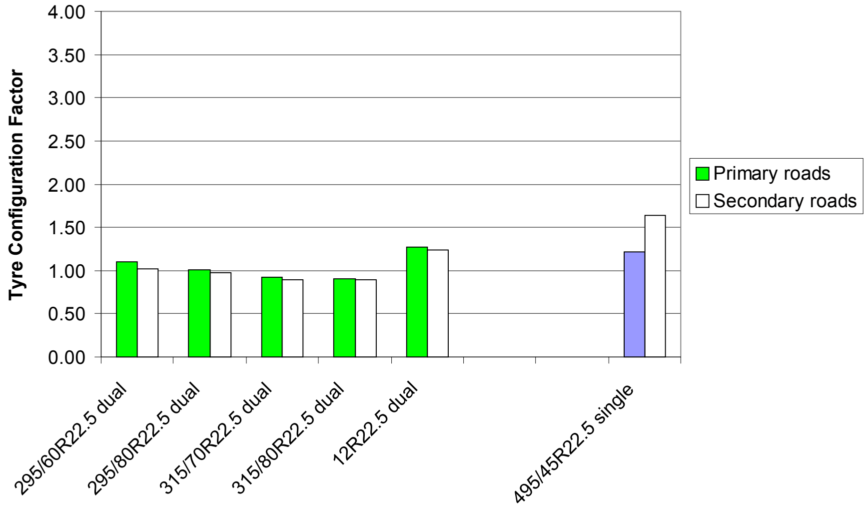


Figure 4.72 - TCF of common current and possible future tyres for driven axles

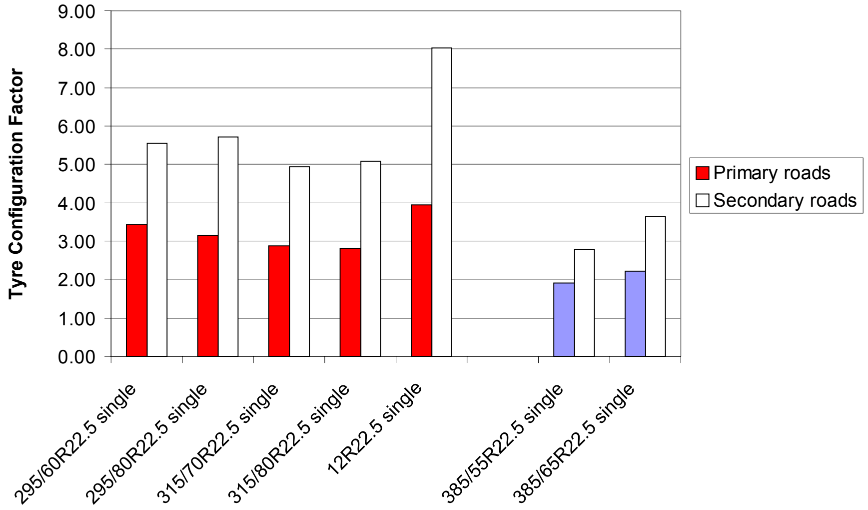


Figure 4.73 - TCF of common current and possible future tyres for steering axles

4.8.6 Specification of roadfriendly tyres by limiting the TCF value

4.8.6.1 General

The TCF values presented in Tables 4.63 to 4.65 relate the pavement wear of a given tyre to the pavement wear of the reference tyre. The Tables show that within a given axle category (towed, driven or steered) there is a wide range of values. This demonstrates the fact that with respect to the effect on pavement wear there are tyres that are more road-friendly, and others that are less road-friendly. Since less road-friendly tyres (those having higher TCF values) will lead to higher pavement maintenance costs, and on the basis that this should, wherever possible, be avoided, it is reasonable to consider placing limits on the TCF value of tyres for a given type of usage.

In this section, proposals are presented for such limiting values, from the point of view of pavement maintenance costs. In Chapter 7, other effects will also be treated, such as possible differences in rolling loss, which affects the fuel consumption and gaseous emissions of vehicles.

In concept, the simplest approach would be to place a maximum limit on the TCF value, irrespective of the load level at which the tyre is used. However, since higher axle loads produce disproportionally higher pavement wear, (see section 4.3.8.3), it can be argued that the TCF limit should be more restrictive for higher axle load levels.

To overcome these problems, and to allow better discrimination between different tyre sizes, the following approach has been adopted:

- base the TCF limits on the damage contribution of a single passage of a given tyre size with a given axle load,
- correlate the proposed TCF limits to the values of the recently developed and possible future tyre types, and to what is technically possible and economically desirable.

4.8.6.2 The damage contribution for current and possible future tyre types

The damage contribution of a single passage of the axle is expressed by the so-called Axle Wear Factor (AWF). This Axle Wear Factor, (see section 4.3.8.3) is a dimensionless factor relating the damage contribution of the specific tyre at a given axle load to the damage contribution of a single passage of the reference tyre with the reference axleload of 10 tonne.

In order to proceed with this approach, it is first necessary to make the following simplifications, in order to maintain reasonable accuracy, while avoiding unnecessary complication. These simplifications are:

- TCF values are used that are based on the "diameter model" description, using the tyre footprint width information collected by ETRTO,
- Correction factors for load imbalance and dynamic effects in the TCF formula should be ignored, since they add only about 1% of additional precision to the calculation of TCF,
- Only primary roads are considered, so that only primary rutting is taken into account, which implies a power of 2 in the Load Equivalency Factor,
- The value of the factor for Axle Configuration is assumed to be equal to unity (1). It is generally accepted (OECD, 1983) that tandem or triple axles with axle spacings below 1.4 m, cause (slightly) more damage than two, or three passages, respectively, of a

single axle of equivalent loading. For primary rutting, however, no specific information is available, and a factor of unity appears to be reasonable.

- The value of the factor for Suspension Configuration is also assumed to be unity (1). Strictly, this value is valid only for those axles having air suspension, but since this is the case for most of the heavy goods vehicles under consideration, the assumption is again reasonable.
- The traction effects of the drive axle on pavement wear are ignored.

Using these simplifications the formula for Axle Wear Factor becomes :

$$\text{AWF} = \text{TCF} \times \text{LEF} = \text{TCF} \times (\text{Axle Load} / 10)^2$$

In the following Table an overview is given of the Axle Wear Factor values for a wide variety of currently available and possible future tyre types. Because of the simplifications used, as described above, some minor differences in TCF values occur, when compared with those given in Tables 4.63 to 4.65. These differences are not sufficient, however, to affect the overall conclusions. It should be noted that no AWF values are given for load levels above the maximum ETRTO-recommended level.

The values in the Table show clearly the effect that at higher load levels the impact on pavement wear increases. This is due to the operation of the exponential power 2 in the LEF.

From the calculated AWF values in Table 4.67, it can be concluded that:

- for the towed axles, with one exception, all tyres have AWF values below or equal to 1.88. The exception is an older generation tyre, namely the 9.5R17.5 tyre, mainly used for low floor trailers. Most of the recently developed wide base single tyres, such as the 385/55R22.5 and 385/55R19.5 tyre, show values below 1.64.
- for the driven axle, the modern generation tyres have all values below or equal to 1.45, whereas the older generation tyres, such as the 10, 11, or 12R22.5 tyre, have higher values. The prototype wide base single tyre 495/45R22.5 shows an AWF value of 1.63.
- for the steering axle, almost all tyres show values below or equal to 1.82. Only the older generation tyres, the use of which is declining significantly, namely the 11, 12 and 13R2.,5 tyre, have values above this limit (1.88, 1.94 and 2.12 respectively). For the recently developed wide base single tyres, such as the 385/55R22.5 and 385/55R19.5 sizes, much lower values are found, ranging from 1.56 to 1.64.

Table 4.67 Values of Axle Wear Factor, expressing the damage contribution of a single passage of a given tyre with a given axle load, referred to the damage contribution of a single passage of the reference tyre with an axle load of 10 tonne. In blue the cells are marked with AWF values above 1,65

						OVERVIEW AXLE WEAR FACTOR						
						axle loading in tonne						
tyre size	**dual/single**	**contact area width**	**dia-meter**	**max load**	**TCF**	**6.5**	**7**	**7,5**	**8**	**9**	**10**	**11.5**
towed axles												
9.5R17.5	dual	352	840	10.3	2.09	**0.88**	**1.02**	**1.17**	**1.34**	**1.69**	**2.09**	
205/65R17.5	dual	350	711	6.2	2.54	**0.98**[a]						
215/75R17.5	dual	350	767	8.2	2.33	**0.99**	**1.14**	**1.31**	**1.49**			
235/75R17.5	dual	400	800	10.3	1.79	**0.75**	**0.88**	**1.00**	**1.14**	**1.45**	**1.79**	
245/70R17.5	dual	430	789	10.3	1.61	**0.68**	**0.79**	**0.91**	**1.03**	**1.30**	**1.61**	
245/70R19.5	dual	400	839	9.4	1.69	**0.72**	**0.83**	**0.95**	**1.08**	**1.37**		
265/70R19.5	dual	420	872	10.3	1.50	**0.63**	**0.73**	**0.84**	**0.96**	**1.21**	**1.50**	
285/70R19.5	dual	420	900	11.6	1.44	**0.61**	**0.71**	**0.81**	**0.92**	**1.17**	**1.44**	
10R22.5	dual	372	1017	10.6	1.54	**0.65**	**0.75**	**0.87**	**0.98**	**1.25**	**1.54**	
11R22.5	dual	368	1054	11.6	1.51	**0.64**	**0.74**	**0.85**	**0.96**	**1.22**	**1.51**	
385/55R19.5	wide base	293	919	8	2.56	**1.08**	**1.25**	**1.44**	**1.64**			
385/55R22.5	wide base	329	998	9	1.93	**0.81**	**0.94**	**1.08**	**1.23**	**1.56**		
385/65R22.5	wide base	285	1071	9	2.25	**0.95**	**1.10**	**1.27**	**1.44**	**1.83**		
425/65R22.5	wide base	308	1126	10.3	1.88	**0.79**	**0.92**	**1.05**	**1.20**	**1.52**	**1.88**	
445/45R19.5	wide base	380	895	8	1.71	**0.72**	**0.84**	**0.96**	**1.10**			
445/65R22.5	wide base	340	1155	11.6	1.55	**0.65**	**0.76**	**0.87**	**0.99**	**1.25**	**1.55**	
drive axles												
295/60R22.5	dual	488	924	12	1.09					**0.89**	**1.09**	**1.45**
295/80R22.5	dual	470	1059	12.6	1.00					**0.81**	**1.00**	**1.32**
315/70R22.5	dual	506	1024	13.4	0.92					**0.74**	**0.92**	**1.22**
315/80R22.5	dual	494	1085	13.4	0.90					**0.73**	**0.90**	**1.19**
10R22.5	dual	372	1017	10.6	1.54		**means >1.65**			**1.25**	**1.54**	**1.73**[a]
11R22.5	dual	368	1054	12.6	1.51					**1.22**	**1.51**	**1.99**
12R22.5	dual	402	1085	13.4	1.26					**1.02**	**1.26**	**1.67**
495/45R22.5	wide base	427	1013	11.6	1.23					**1.00**	**1.23**	**1.63**
steering axle												
295/60R22.5	single	244	924	6.5	3.44	**1.45**						
295/80R22.5	single	235	1059	7.1	3.14	**1.33**	**1.54**					
315/70R22.5	single	253	1024	7.1	2.89	**1.22**	**1.41**	**1.62**				
315/80R22.5	single	247	1085	8	2.81	**1.19**	**1.38**	**1.58**	**1.80**			
11R22.5	single	184	1054	6.3	4.72	**1.88**[a]						
12R22.5	single	201	1085	7.1	3.95	**1.67**	**1.94**					
13R22.5	single	218	1125	8	3.32	**1.40**	**1.63**	**1.87**	**2.12**			
385/55R19.5	wide base	293	919	8	2.56	**1.08**	**1.25**	**1.44**	**1.64**			
385/55R22.5	wide base	329	998	9	1.93	**0.81**	**0.94**	**1.08**	**1.23**	**1.56**		
385/65R22.5	wide base	285	1071	9	2.25	**0.95**	**1.10**	**1.27**	**1.44**	**1.83**		

a) AWF value for maximum ETRTO-recommended load level

It should be noted once more that the figures of Table 4.67 are valid for the present tyre sizes, with the mean tread width and diameter provided by the ETRTO. It must be understood that an evolution of these parameters may change the TCF and AWF values for different tyre types of a given tyre size.

For instance, if the tyre size 385/65R22.5 (wide base single, towed axles) is considered and if one or several tyre manufacturers sell the types A, B, C and D with a diameter of 1071 mm and tread widths of the respective following values, 285, 300, 305 and 310 mm.

The TCF and AWF values for a 9 tonnes axles would be given by table 4.68. In this example, for an axle load of 9 tonnes, the Axle Wear Factor is above 1.65 for types A and B, and below 1.65 for types C and D.

Table 4.68 Examples of TCF and AWF for a 9 tonnes axle for different 385/65R22.5 tyre types.

	A	B	C	D
Diameter (mm)	**1071**	**1071**	**1071**	**1071**
Tread width (mm)	**285**	**300**	**305**	**310**
TCF	**2.25**	**2.07**	**2.02**	**1.96**
AWF for a 9 tonnes axle	**1.83**	**1.68**	**1.63**	**1.59**

4.8.6.3 Proposed TCF limits

It is recommended that limits on TCF are placed on the design of new tyre types, on further development of existing tyres for existing vehicle types, and also for all tyres for new vehicle types. Based on the AWF values of the recently developed tyres, as given above, a limiting AWF value of 1,65 for all axle types is recommended.

Having fixed the AWF value, , the TCF limiting values can be calculated for different axle load levels, using the formulae of Table 4.69. The corresponding TCF values are reported in Table 4.70.

Table 4.69 Summary of formulae used

BASIC FORMULA	
Axle Wear Factor	AWF = TCF x LEF
Tyre Configuration Factor	$TCF = (width / 470)^{-1,65} \times (diameter / 1059)^{-1,12}$
Load Equivalency Factor	$LEF = (load / 10)^2$
LIMIT VALUES	
Axle Wear Factor	$AWF_{max} = 1,65$
Tyre Configuration Factor	$TCF_{max} = AWF / LEF = 165 / (load)^2$
Allowable Load (tonne)	$Load_{max} = SQRT\ [165 / TCF] = SQRT\ [165 /\{(width / 470)^{-1,65} \times (diameter / 1059)^{-1,12}\}]$

Table 4.70 Proposed TCF limits (rounded to nearest 0,05) in relation to applied axle load based on limiting value of AWF=1,65 and the formulae of Table 4.69

		Axle load in tonne						
		6,5	7,0	7,5	8,0	9,0	10,0	11,5
Proposed TCF limit*								
all axles types: ie. steering, driven and towed	**AWF$_{max}$=1,65**	**3,90**	**3,35**	**2,95**	**2,60**	**2,05**	**1,65**	**1,25**

* with possible exceptions for tyre sizes having a low market share and for special purpose vehicles, e.g. trucks for public works equipped with 13R22,5 tyres

In Table 4.67 the combinations of tyre and axle load that have TCF values above the proposed limits, are marked in blue. This clearly shows that the concept of TCF limits would not eliminate the use of any of the tyres by itself. It does, however, limit the maximum allowable load level for some specific tyres or impose an evolution of the tyre geometry (diameter and or tread width) from the point of view of pavement wear. As a consequence, in the future development of those tyres presently above the TCF limit, special attention should be paid to their road-friendliness.

4.8.6.4 Maximum design tyre inflation pressure

In addition to the proposed limits on TCF value of the tyre, it is also essential, that a maximum limit be placed on the manufacturer-recommended inflation pressure of the tyre (measured cold) according to the allowable load level of the specific axle on which the tyre is mounted. This will ensure that the TCF limits cannot be inadvertently exceeded by the use of increased inflation pressure.

In principle, the effect of inflation pressure is incorporated in the TCF approach explained above, and there should be no direct need for a limit on the recommended inflation pressure at operating conditions. However, there are two reasons why such a limit would be particularly useful.

First, it must be recognised that the approach to TCF limits described is based on test results of tyres all of which had recommended inflation pressures (measured cold) up to 9 bars. Extrapolation of these results to higher inflation pressures is therefore highy unreliable.

Second, it must also be recognised that the influence of inflation pressure on pavement wear can be approached only indirectly. Since only the TCF formula for primary roads has been used, the results of its use are strictly only valid for primary roads. As a consequence, the proposed limits on TCF are thus not a guarantee that tyres might be developed in future (e.g. with inflation pressures of 10 or 11 bar) that meet the TCF value of primary roads, but which may be very detrimental to secondary roads. Although one option would be to develop separate TCF limits based on the formula for secondary roads, this would make the approach rather complex, and difficult to implement. The addition of a direct limit on inflation pressure is therefore preferred.

The proposed limit on inflation pressure for the design of tyres (measured cold) is 9 bars.

4.8.6.5 Possible means of implementation

At present, there are no EU regulations of vehicle weights and dimensions that cover the matter of "road-friendly" tyres on heavy freight vehicles. In chapter 8 the different options for implementation into regulations will be considered.

In general, the principles of implementation into the appropriate regulation(s) could be as follows:

- Include TCF limits in the appropriate legislation. The tyre and vehicle industries will need an agreed period in which to adapt and focus their efforts on new tyre design and tyre construction to meet the limits.
- A period should then be negotiated with the tyre and vehicle industry to allow the sale of existing, stocked, vehicle types (especially with respect to the tyre mounting).
- Finally, negotiations with the tyre and vehicle industry should establish a time period for the sale of tyres that do not meet the proposed TCF limits.

4.8.6.6 Concluding remarks

Finally it should be emphasised that in addition to the effect on pavement wear, the effects of rolling losses of tyres, which govern the fuel consumption and gaseous emissions from the vehicle, are also of considerable importance. The TCF limits related to pavement wear should therefore be looked upon only as a first step.

Further research and development work should allow the TCF concept to take into account the effects of tyre type on fuel consumption, vehicle emissions, safety, tyre mass and diameter. A first attempt is described in chapter 7.10, where an index of the overall tyre economic efficiency was built. It considers the pavement maintenance, fuel consumption, gaseous emissions, payload and recycling. It allows to determine if the introduction of a new tyre size would, when compared to a reference one, result in an overall societal cost or benefit. It could become the basis for a future tyre approval procedure.

Based on the knowledge gathered in COST 334 concerning the relation between tyre design and pavement wear, it is considered that new research is necessary on new vehicle/tyre concepts. The guiding principle of such work should be to examine the total effect on pavement wear, fuel consumption and emission, as well as the possible effects on noise generation, etc., per tonne of payload. It is expected that by studying these elements in an integrated way a valuable contribution will be taken towards more efficient heavy goods road traffic, taking into account economic and societal costs.

4.9 SUMMARY, CONCLUSIONS AND RECOMMENDATIONS

4.9.1 Summary of the work of TG3

As part of the overall work of COST 334, Task Group 3 (TG3) ‘Pavement Wear Effects’ has carried out a programme of experimental and computational research and information gathering in order to investigate the relative effects of single tyres, wide base single tyres and dual tyres on the wear of pavement structures.

On the basis of earlier work, the OECD (1982, 1988) has previously stated that an axle with wide base single tyres inflicts about equal pavement damage as two (1.2^4) axles with dual tyres and the same axle load. This value is clearly based on specific tyre sizes and is unlikely to be generally applicable to other tyre sizes. The principal objective of TG3, therefore, was to determine this value for modern tyre types, to relate it to tyre characteristics such as size and inflation pressure, and to determine a means of calculating relative effects of current and future tyre types.

As a first step, TG3 identified the most relevant aspects of tyre-pavement interaction, with respect to pavement wear, on which to focus its study, assessed the available research methods and examined the data already available. The following questions emerged from this first phase:

- What are the general characteristics of truck traffic in Europe, in respect of: vehicle type, number of axles, axle and wheel loads?
- What are the pavement types that are relevant for the European situation and what are the relevant distress modes for the different climates and pavement structures?
- What are the stresses in the tyre - pavement interface?
- Which methods can be used to determine (quantitatively) the relative effects of tyres on pavement wear?

A literature review carried out specifically to address these questions concluded that a better understanding of the tyre-pavement interaction parameters leading to pavement wear was limited by a lack of appropriate data. In more than thirty detailed literature references, only limited quantitative data on relative pavement wear effects was found, particularly for permanent deformation of bituminous layers, which was identified as the dominant distress mode for European primary roads. The literature review did indicate, however, that TG3 should:

- focus on bituminous (fully flexible and composite) pavements, distinguishing three pavement types:
  - thin pavements, with a thickness of bituminous layers of 100 mm or less,
  - medium pavements, with a bituminous thickness of around 200 mm,
  - thick pavements, with bituminous thickness of around 300 mm and more.
- concentrate on three pavement distress modes:
  - fatigue cracking, being cracking in the bituminous or cement bound material originating at the bottom of the respective layers, due to fatigue of the material by repeated bending due to the application of a large number of wheel loads This

occurs mainly on relatively weak / thin pavements (Visible cracking in thick pavements is likely to originate (at least partly) at the surface.)

  - rutting due to permanent deformation of bituminous layers, defined in this report as 'primary rutting'. This occurs most often on principal roads with thick and medium bituminous layers, and is made worse by high pavement temperatures.
  - rutting due to permanent deformation in the subgrade or in granular layers below the bituminous layers, defined in this report as 'secondary rutting'. This occurs mainly on relatively weak / thin pavements.
- Assume that the average contact stress over the tyre footprint area would suffice for the analysis of the distress modes considered. Analysis of the literature on tyre-pavement interface stresses concluded that available data on the detailed stress distribution is very incomplete.

Because of the extent of the lack of data, TG3 therefore decided to perform a considerable amount of new research within the short time available. The programme of research was guided by eleven specific research questions, grouped into three categories:

- general information on tyre parameters,
- the behaviour of the tyre-pavement interaction under controlled conditions,
- the translation of the previous behaviour to in-service conditions.

TG3 decided not to perform a study into the effects of different load magnitudes, but to concentrate on the effects of different tyres at equal axle loads. Generally a 4th-power law is accepted for load equivalency, though TG3 used more detailed power factors (2 for primary rutting, 4 for secondary rutting, 4 to 5 for fatigue of bituminous layers) in its analysis of relative effects of tyre sizes. Besides the influence of axle load, TG3 also excluded the effects of axle configuration (single, tandem or tri-axle) and vehicle suspension type from tyre-related factors.

The experimental plan developed and executed by TG3 incorporated laboratory tests, full scale experiments, field tests and numerical studies. These were contributed by the participating countries, who also provided funding. In the full scale experiments, pavement response (stresses and strains generated in the pavement by the passage of different wheel load configurations) was distinguished from performance (development of distress due to a large number of passages of a given wheel load).

The data from literature and from the TG3 experiments were combined into one data base. From regression analyses of this data base, TG3 developed a set of formulae for the so called Tyre Configuration Factors (TCF). The TCF of a tyre expresses the amount of pavement wear relative to an arbitrarily chosen reference tyre. The TCF is partly dependent on tyre size parameters and partly dependent on the loading and inflation conditions of the tyre. It excludes influences of axle load, axle configuration and vehicle suspension type. Different TCF formulae were obtained for different distress modes and pavement thickness. Despite considerable dispersion in the data, sufficiently good correlations were achieved, leading to reasonably accurate predicted results from the formula (see section 4.5.10). Additional analyses were executed to quantify aspects such as the effect of lateral wander, tyre dynamics and unequal load sharing in dual tyre assemblies, see sections 4.5.8, 4.6 and 4.7.

The TCF can be used to quantify the relative amount of distress caused by different tyre configurations, depending on the pavement thickness and distress mode considered. TCF values were calculated as an example for several tyre types. Sensitivity analyses of the TCF values were executed for variations in relevant parameters such as tread pattern width, tyre-pavement contact area, tyre diameter and over-inflation. Because the TCF relies on tyre-related parameters, it may be used to calculate the distress caused by current and future tyres, relative to the adopted reference tyre.

Finally, TG3 examined and assessed the possible use of simple criteria, based on the TCF, that might be used to limit pavement wear. These criteria may equally well be used to guide the development of new tyre types.

4.9.2 Conclusions

The conclusions of the work carried out by TG3 are confined to the relative damaging effects of different tyre sizes on road pavements. Many different complex and inter-related factors have been identified as contributing to pavement distress, and these have been described earlier. In the following paragraphs, therefore, an attempt has been made to separate the overall conclusions of the work into general conclusions, those related to the tyre concept and tyre width, size of contact area, tyre inflation pressure and contact stress distribution and those related to the relative pavement wear of the current tyres. The interaction between many of these conclusions should, however, be remembered.

The work of the Task Group was confined to bituminous pavements. For concrete pavements, TG3 expects only small influences of differences in tyre configurations on pavement wear. For bridges, viaducts, etc. no conclusions were drawn.

General

1. Large differences in relative pavement wear exist among dual tyre assemblies and among wide-base single tyres. Therefore, a single factor for the difference between wide-base single and dual tyres is not applicable. Comparisons between pavement wear effects can only be made if the detailed characteristics of the tyre fitments are taken into account.
2. The pavement wear effects of different tyres vary according to the types and thickness of pavement, as well as their associated distress modes. For this reason COST 334 developed the concept of the Tyre Configuration Factor (TCF). The TCF of a tyre expresses the amount of pavement wear, depending on the pavement thickness and distress mode considered, relative to an arbitrarily chosen reference tyre. In use, the higher the TCF value, the higher the pavement wear (with the same axle loads, suspension type, etc.).
3. The TCF formulae developed from the work enable the quantification of the pavement wear effects of current and future different tyre fitments and sizes. The derivation of TCF formulae for all pavement thicknesses was not possible in all cases, however, because of insufficient data.
4. On the basis of the TCF formulae, the main influencing factors for pavement wear are the width (see Conclusions 6 and 7) and size of the tyre-pavement contact area, and the ratio of the actual inflation pressure over the recommended inflation pressure for the actual load (hereafter referred to as the pressure ratio).
5. It was found that the thinner the pavement, the stronger was the influence of differences in tyre configurations on pavement wear.

On the tyre concept (one or two contact areas) and the tyre width parameter:

6. For primary rutting (mainly on thick and medium pavements) the main width parameter is Width, being the footprint width for wide base singles, and for dual tyres twice the footprint width of the individual tyres. (All width values consider footprint (tyre contact area envelope) width, not tyre section width.) As a consequence, for this distress mode, pavement wear due to wide base single tyres or dual tyre assemblies does not differ significantly, when the axle load, tread pattern width, contact area, tyre diameter and pressure ratio are equal.

7. For secondary rutting and fatigue cracking on thin and medium pavements the main width parameter is the Total Width of the footprint of the tyre assembly. [For dual tyre assemblies this includes the distance (100mm) between the footprints of the individual tyres.]. As a consequence, single and dual tyre assemblies will produce equal TCF values indicating equal pavement wear, when the Total Width is equal (all other factors being equal). Usually, however, for the same axle load, current dual tyres will have a greater Total Width than a current wide single tyre.

8. For secondary rutting and fatigue cracking on thick pavements there is little difference between different fitments and sizes of tyres, as the pavement wear is dominated by the overall magnitude of the load carried in these cases.

On size of contact area:

9. In addition to its width, the length of the tyre-pavement contact area was shown to be influential in the cases of primary rutting on thick (and probably thin and medium) pavements and fatigue on thin and medium pavements. Combined, this signifies the influence of the size of the tyre-pavement contact area, and hence the average contact stress. Sensitivity analysis showed that a decrease of 10% in contact area results in a 9-39% increase in pavement wear for these cases. No similar conclusion could be drawn for secondary rutting because of a lack of data.

10. The tyre diameter can also be taken as an indicator for the contact area length and the related pavement wear. A reduced tyre diameter will lead to increased pavement wear (when all other tyre parameters remain constant). This is important in the context of a trend towards the use of smaller-diameter tyres in Europe, to allow the lower platform heights that will accommodate volume-limited loads to be carried, rather than mass-limited loads

On tyre inflation pressure and contact stress distribution:

11. The tyre inflation pressure is not a direct parameter in the TCF formulae. For the same load and tyre, higher inflation pressures generally result in a smaller tyre-pavement contact area, and thereby increased surface stress in the pavement As a consequence, higher inflation pressures generally result in higher pavement wear, especially on thin pavements.

12. The ratio of actual to recommended inflation pressure was shown to be influential for the cases of primary rutting on thick (and probably medium) pavements and secondary rutting on thin and medium pavements. An inflation pressure 10% higher than that recommended for the actual tyre load results in about 15% increase in pavement wear. In such a case of over-inflation, the contact stress distribution is non-uniform and the load is concentrated on a smaller area.

13. The detailed contact stress distribution within the contact area is probably relevant for distress modes whose origin is at or close to the pavement surface, such as ravelling (loss of aggregate in the pavement surfacing) and surface cracking. Although COST

334 established good techniques for the measurement of these distributions, insufficient data was obtained to draw robust conclusions.

On the effect of dynamic loading and load imbalance

14. By comparison with other effects, tyre fitment does not significantly affect the dynamic loading of the road pavement.

    Experimental work reported by COST 334 shows that, for the tyre fitments tested, the dynamic loading applied by the truck is not changed significantly by the choice of tyre fitment. Dynamic loading can significantly increase pavement damage, and it had been thought that the contribution of tyre stiffness to the suspension characteristics controlling the phenomenon may be a significant factor. On the basis of the work carried out, this appears not to be the case.

15. By comparison with other effects, the effect of load imbalance between tyres on a dual assembly was found not to significantly affect pavement wear or other aspects.

    Load imbalance between tyres on a dual tyre assembly is brought about primarily by different inflation pressures in each of the tyres, and by truck axle geometry and pavement profile. Surveys have shown that this difference (in relation to the recommended inflation pressure) can be large, but is confined to a small proportion of the truck fleet. The work of COST 334 has shown that load imbalance effects on pavement wear and other aspects is negligible in comparison with other effects.

On TCF values for current common tyre fitments and possible future tyre fitments

As stated earlier, TCF values vary according to the pavement thickness and distress mode under consideration. For practical use, values for the current common and possible future tyres (rim sizes 19.5 and 22.5 inches) were determined for the European primary road network (based on primary rutting in the bituminous layers of thick pavements) and the European secondary road network (based on a weighted average of the three distress modes on medium pavements, namely primary rutting, secondary rutting and fatigue cracking). Most road freight in Europe is carried on the primary networks, however, and greater importance is attached to these.

16. Common current and possible future dual tyre assemblies for towed axles have TCF values for primary roads ranging from 1.5 to 1.7 and for secondary roads TCF values of 1.3 to 1.5. Current common and possible future wide base single tyres for towed axles have TCF values for primary roads ranging from 1.5 to 2.2 and for secondary roads TCF values ranging from 2.2 to 3.6. On average the use of current common or possible future wide base singles on towed axles, instead of dual tyre assemblies, increases the contribution of these axles to pavement wear on primary roads and secondary roads by 17% and 97%, respectively.

17. Common current and possible future dual tyre assemblies for driven axles have TCF values for primary roads ranging from 0.9 to 1.3 and for secondary roads TCF values ranging from 0.9 to 1.2. The prototype extra-wide base single tyre 495/45R22.5 for use on drive axles has a TCF value of 1.2 on primary roads and 1.6 on secondary roads. On average, the use of wide base singles on driven axles, instead of common current dual tyre assemblies, increases the contribution of these axles to pavement wear on primary roads and secondary roads by 17% and 64%, respectively.

18. Conventional single tyres for steering axles have TCF values for primary roads ranging from 2.8 to 4.0 and for secondary roads TCF values ranging from 5.0 to 8.0. Current common and possible future wide base single tyres (from the 385 - fitment

and wider) for steering axles have TCF values for primary roads of 1.9 to 2.2 and for secondary roads TCF values of 2.8 to 3.6. On average the use of current common and possible future wide base singles on steering axles reduces the contribution of this axle to pavement wear on primary and secondary roads by 36% and 45% respectively.

19. Conventional single tyres for steering axles are relatively more damaging than the common dual tyre assemblies for driven and towed axles, and wide single tyres for towed axles. This is partly alleviated by lower loads on the steering axles, but in practice the steering axle still may cause more pavement wear than a driven or towed axle.

On Axle Wear Factors for the different axle types fitted with current common and possible future tyres.

Based on the TCF value of tyres, the damage contribution of a single passage of an axle can be calculated using the appropriate formula, taking into account the actual axle load. This damage contribution is expressed as the number of passages of the reference tyre with the reference load of 10 tonnes, that gives the same amount of damage. This number is called the Axle Wear Factor (AWF). For the current common and possible future tyre sizes (for rim sizes 19.5 and 22.5 inches), AWF values were determined for different axle loads for the European primary road networks.

20. Current common and possible future tyre assemblies for the driven axle, either with duals or wide base singles, have, at a load level of 11.5 tonne, AWF values ranging from 1.2 to 1.7. Current common and possible future tyre sizes for the towed axle, either with duals or wide base singles, have, for their respective maximum allowable load levels (between 8 and 10 tonne), AWF values ranging from 1.1 to 1.9. This range of values is very similar to that for the driven axle. Finally, current common and possible future tyres for the steering axle, fitted with either conventional singles or wide base singles, have, at their respective maximum allowable axle load (between 6.5 and 9 tonne), AWF values ranging from 1,4 to 1,9. This range is marginally higher than that for the driven axle. That the lower level of the axle loads on the towed axles is not reflected in lower AWF values, is explained by the fact that generally, relative to the axle load, wider tyres are used on the driven axle. The marginally higher AWF values of the steering axle, though having a much lower load in comparison with the driven axle, is explained by the fact that on the steering axle, all load must be transferred by two tyres, whereas for the driven axle, four tyres are usually used.

4.9.3 Recommendations

On the basis of the conclusions noted above, a number of recommendations can be made. These apply to the use of the experimental and analytical results obtained on the relative pavement wear effects of different tyres in the wider work of COST 334, and to the specific case of those effects as they arise in practice.

1. *On the use of results in the further work of COST 334*

   TG3 recommends the use of the TCF formulae it has developed, to quantify the relative effects of different tyre load configurations on the wear of pavement structures. These factors may be used to calculate the contribution of pavement wear of different tyre types in the overall assessment of the use of wide single and dual tyres.

2. *On the use of tyre parameters in road pavement design.*

The development of the Tyre Configuration Factor allows discrimination between different tyre fitments based on the corresponding damage they cause to road pavements. It is recommended, therefore, that the TCF should be used by national road authorities in the design process to better estimate the damaging effect of the traffic that roads are designed to carry.

Implementation of this recommendation will require that the design authority undertakes appropriate surveys of the national fleet of road transport vehicles, to establish the numbers and types of vehicle, their tyre equipment, and other factors. Approximations can of course be made by the judicious use of sample surveys, the results of which are extended to the national situation. Alternatively, specific surveys may be carried out for the design of a given road.

3. *On the application of the Tyre Configuration Factor to tyre design and use*

The results of the COST 334 work show that the use of a limit on TCF can be used to guide the design of new tyre sizes, and the further development of existing tyre sizes. It is recommended, therefore, that limiting values of TCF be placed on new and developing tyre fitments.

The limits to be used should be as follows:

Proposed TCF limits (rounded to nearest 0,05) for axle types in relation to applied axle load

		Axle load in tonne						
		6.5	7.0	7.5	8.0	9.0	10.0	11.5
TCF limits								
Proposed limit*								
all axle types: ie. Steering, driven and towed	AWF=1.65	**3.90**	**3.35**	**2.95**	**2.60**	**2.05**	**1.65**	**1.25**

* with possible exceptions for tyre sizes having a low market share and for special purpose vehicles, such as the 13R22.5, mainly fitted on public works trucks.

COST 334 believes that these limits should be implemented into appropriate EU legislation. In general, the principles of implementation into the appropriate legislation could be as follows:

a) Include TCF limits in the appropriate legislation. The tyre and vehicle industries will need an agreed period in which to adapt and focus their efforts on new tyre design and tyre construction to meet the limits.

b) A period should also be negotiated with the tyre and vehicle industry to allow the sale of existing, stocked, vehicle types (especially with respect to the tyre mounting).

c) Finally, negotiations with the tyre and vehicle industry should establish a time period for the sale of tyres that do not meet the proposed TCF limits.

4. *On Maximum Designed Operating Tyre Inflation Pressure*

   In addition to the proposed limits on TCF value of the tyre, it is also recommended that a maximum limit be placed on the manufacturer-recommended inflation pressure of the tyre (measured cold) according to the allowable load level of the specific axle on which the tyre is mounted. This will ensure that the TCF limits cannot be inadvertently exceeded by the use of increased inflation pressure.

   The proposed maximum designed operating tyre inflation pressure (measured cold) is 9 bars.

   Much progress has been made in recent years on the development of on-board systems for the measurement and control of tyre inflation pressures. It is further recommended, therefore, that consideration is given to introducing legislation requiring the use of such systems on the largest (5 and 6-axle) vehicles, in order to ensure compliance with tyre manufacturer's recommended inflation pressures for given loads and duty cycles. This will produce benefits to operators in terms of improved tyre performance (tyre wear and rolling resistance), and to society in terms of minimised pavement wear and reduced safety risks.

5. *On future research on the Tyre Configuration Factor*

   The work of Task Group 3 has been necessarily limited to a proportion of the combinations of tyre type, pavement type, and pavement distress modes that need to be considered. Among a number of other issues, it is recommended that further research is carried out, as a priority, on:

   - The effects of different tyre load configurations on concrete pavements, bridges, viaducts, etc. It is anticipated that the influences of tyre type will be strongly dependent on the materials and structural designs used. Further research is necessary to expand the present work to other types of structure.
   - The separation of the effects on thin and medium pavements of different tyre load configurations.
   - Comparative testing of actual pavement performance in respect of fatigue and secondary rutting, to validate the present predictions based on pavement response instead of performance.
   - The effects of tyre dynamics with different types and sizes of tyres, on pavements of differing thicknesses.
   - The refinement and expansion of the TCF formulae developed by TG3.

6. *On future development of truck tyres*

   The results of the work provide useful guidance to tyre manufacturers on how tyres might be developed to limit pavement distress. Tyre manufacturers are not only concerned with this issue, of course. TG3 acknowledges that the properties of a given tyre size, including its contact area, are the results of an equilibrium between many performances including adherences (dry, wet, snow, ice …), noise, fuel consumption, treadwear, vehicle handling. All these factors have to be taken into account.

   - Nevertheless, from the point of view of pavement distress alone, it is recommended that future truck tyres are developed with limited TCF values. This can be achieved in particular by providing sufficient width and length of the tyre-pavement footprint area.

- From the same viewpoint it is recommended that the existing 385/65R22.5 tyre size be modified to achieve lower TCF values. This can be done by providing a greater width of the tyre footprint area.

4.10 GLOSSARY OF TERMS AND ABBREVIATIONS

AASH(T)O	American Association of State Highway (and Transportation) Officials
AC	Asphaltic Concrete (type of HMA)
ACF	Axle Configuration Factor, factor expressing the relative pavement wear of an axle load, when incorporated in a tandem axle or tri-axle configuration, relative to that same axle load when single, see section 4.3.8.3
AGRAC	cement bound asphalt granulate (NL, material for bound base / subbase)
AI	Asphalt Institute (United States of America)
ALF	Accelerated Loading Facility (Australia, United States of America)
ALT	Accelerated Load Testing of pavements
articulated vehicle	(heavy goods) vehicle that consists of two parts with a hinging a connection (e.g. a truck-trailer or tractor-semitrailer combination)
aspect ratio	ratio of tyre height (distance between rim and tread surface) over tyre section width, usually expressed in percent
axle configuration	single axle, tandem axle or tri-axle
axle load	load on a single axle (The axle load is the sum of the two wheel loads.)
axle	rod upon which a wheel turns, connecting the centres of a pair of wheels on either side of a vehicle (Sometimes the middle part of an axle is replaced by the vehicle body.)
base	= roadbase
BASt	Bundesanstalt für Straßenwesen (German Federal Highway Research Institute)
bit.	bitumen
CA	Crushed Aggregate
CAPTIF	Canterbury Accelerated Pavement Testing Indoor Facility (New Zealand)
CBR	California Bearing Ratio
crack	generally: line of division where something is broken. but not into separate parts. In pavement engineering, the latter restraint is dropped, and cracks can completely break up a pavement into segments.
cracking	development of cracks. Four types are distinguished: fatigue cracking, thermal cracking, surface cracking and reflective cracking.
DAC	Dense Asphalt Concrete (NL, type of HMA for surface courses)

DBM	Dense Bitumen Macadam (UK, type of HMA for base and binder courses)
distress	reduction of pavement quality due to loading by traffic and/or climate. Several types of distress exist, of which the main types considered in this report are: primary rutting, secondary rutting, fatigue cracking, surface cracking, thermal cracking, reflective cracking and ravelling (see 4.3.5).
DLC	Dynamic Load Coefficient, defined by the OECD as the ratio of the RMS (root mean square) dynamic wheel load to the mean wheel load, i.e. the coefficient of variation of the total wheel load
double axle	a configuration of two axles, with more than 1.8 m spacing. (This is not a tandem axle, and the individual axles of a double axle are considered separately.)
drive(n) axle	axle on which the tyres are driven by the vehicle’s engine. This axle transmits the power of the engine to the pavement.
dual tyre	dual tyre assembly
dual wheel	dual tyre assembly
dynamic load	load (of a vehicle or on an axle, tyre assembly or tyre) which changes in time, caused by vertical movements of the vehicle (In this report, dynamic load comprises the total of the static and dynamic components of the load.)
E_FWD	Stiffness modulus, backcalculated from FWD measurements
EME	Enrobé á Module Elevé (high modulus HMA, France)
ESAL	Equivalent Single Axle Load
fatigue cracking	cracking in the bituminous or cement bound material originating at the bottom of the respective layers, due to fatigue of the material by a great number of repetitions of bending caused by wheel loads, see Figure 4.13. (This definition is common in pavement engineering, and excludes surface cracking and cracking due to thermal cycling, although these are also due to fatigue because of repeated stress cycles.)
fatigue	deterioration of material quality without deformation, due to repeated stress cycles (Essentially these can include both mechanical loadings such as traffic, and stresses induced by thermal cycling. In pavement engineering, however, fatigue is often considered to only arise from mechanical loading.)
fifth wheel	component of the hinging connection between tractor and semitrailer (see Figure 4.5), carrying part of the semitrailer weight
flexible pavement	pavement of which the main structural layers are composed of bituminous and/or unbound granular materials
footprint	‘envelope area’ or ‘gross contact area’ between tyre and pavement, including both the area of the tread grooves (sipes) and the ‘net contact area’ between tyre rubber and pavement.

FORCE	First OECD Road Common Experiment
FWD	Falling Weight Deflectometer, device measuring the resilient surface deflection of a pavement under an impulse load, caused by the impact of a falling weight, simulating a moving wheel load
GVW	Gross Vehicle Weight (in t or kN)
HDM	Heavy Duty Macadam (UK, type of HMA, mainly for base courses)
heavy vehicle	vehicle for use on (road) pavements with a gross vehicle weight of more than 15 tonnes (150 kN) on two axles, or more on more axles. This excludes all vehicles for sole use on rails. Heavy vehicles include busses, trucks, lorries, trucks with trailers, tractors with semitrailers.
HGV	Heavy Goods Vehicle (United Kingdom)
HMA	Hot Mix Asphalt. This term will be used loosely in this report to include all pavement mixes of bitumen and mineral aggregates, regardless of bitumen type or grading and type of the mineral aggregate. (Among others, this includes AC, DBM, EME, HDM, HRA, OAC, RBA, SMA, STAC, UTAC.)
HRA	Hot Rolled Asphalt (UK, type of HMA, mainly for surface courses)
kcycles	thousand load repetitions
kingpin	component of the hinging connection between tractor and semitrailer (see Figure 4.5), carrying part of the semitrailer weight
lateral wander	transversal distribution of the positions of wheel loads over a carriageway or traffic lane
LCPC	Laboratoire Central des Ponts et Chaussées (France)
LEF	Load Equivalency Factor, factor expressing the relative pavement wear of an axle load, as a function of the load size only (relative to a reference value), see section 4.3.8.3
LNEC	Laboratório Nacional de Engenharia Civil (Portugal)
load imbalance	unequal load division between both tyres of a dual tyre assembly (see 4.3.6.6)
load	force acting between a vehicle (or an axle, tyre assembly or tyre) and the pavement. Often, only the vertical forces are considered, but also longitudinal and lateral horizontal forces can occur, due to acceleration, deceleration, steering, ascent or descent of the vehicle and/or inclination of the pavement.
LVDT	Linear Variable Differential Transformer (type of gauge for displacement measurements)
msa	million standard axles of 80 kN (UK)
non-driven axle	= towed axle
OAC	Open Asphalt Concrete (NL, type of HMA for binder courses)
OECD	Organisation for Economic Co-operation and Development

pavement	structure, composed of layers of selected and/or manufactured materials, providing a lasting and adequate surface for vehicle movements
PCC	Portland Cement Concrete
performance	long-term reaction (over years, generally) of a pavement to the summation of a large number of loads, generally described by the development of pavement distress
permanent deformation	change of shape of pavement materials, due to traffic loading, which remains after the loads have passed. This can be due to compaction of granular materials or due to (plastic and viscous) shear flow.
primary rutting	(as defined in this report:) rutting due to permanent deformation of the bituminous layers, see Figure 4.13.
PWR	Pavement Wear Ratio, comprising both PWR_D and PWR_L, where most PWR for primary rutting are actually PWR_D, and most PWR for secondary rutting and fatigue are actually PWR_L.
PWR_D	Distress Ratio, or Pavement Wear Ratio regarding Distress (for a certain load configuration on a certain pavement), ratio of the amount of distress of a certain pavement at a certain number of load repetitions for a certain load configuration (load size, suspension, tyre type, inflation pressure) relative to the amount of distress of that pavement up to the same number of load repetitions for a chosen reference load configuration. See Figure 4.16.
PWR_L	Life Ratio, or Pavement Wear Ratio regarding Life (for a certain load configuration on a certain pavement), ratio of the life of a certain pavement up to a certain distress level for a certain load configuration (load size, suspension, tyre type, inflation pressure) relative to the life of that pavement up to the same distress level for a chosen reference load configuration. See Figure 4.16
ravelling	loss of stones in the surface of the pavement as a result of failure of the bond between the aggregate and the binder by a great number of shear loadings in combination with ageing of the material.
RBA	Road Base Asphalt (FR, type of HMA for base courses)
reflective cracking	cracking of the bituminous layers in a composite structure as a result of cracks in the bound base layer below, see Figure 4.13.
response	short-term reaction (within seconds) of a pavement to an external load, generally specified as the mechanical stresses and strains in the pavement due to the load
rigid pavement	pavement of which the main structural layers are composed of Portland cement concrete (PCC)
rim	circular edge of the (mostly metal) framework of a wheel, on which the tyre is fitted, see Figure 4.4.
road base	pavement layer located below the surface and binder layers, fulfilling a load carrying and distributing function. The road base

	can be a bituminous road base, a granular road base or a cement bound road base.
rpm	revolutions per minute
rut depth	distance between the lowest point of a wheel path and the imaginary straight line drawn between those parts at the surface of the cross-section immediately on either side of the wheel path
rut	a depression in the pavement surface along the wheel paths, typically with a width of several decimetres and a length of tens to thousands of meters
rutting	the development of ruts in the pavement surface. Two types are distinguished, which in this report are called primary rutting and secondary rutting.
SBS	Styrene-Butadiene-Styrene polymer modifier for bitumen
SCF	Suspension Configuration Factor, factor expressing the relative pavement wear of an axle load with a certain suspension type, relative to an axle with a reference (air) suspension, see section 4.3.8.3.
secondary rutting	(as defined in this report:) rutting due to permanent deformation of the granular layers below the asphalt layers or of the subgrade, see Figure 4.13.
semitrailer	trailing, unpowered, part of a tractor-semitrailer combination. A tractor is connected to the semitrailer by the kingpin and fifth wheel. (see Figure 4.5)
SMA	Stone Matrix Asphalt, or Stone Mastic Asphalt (type of HMA, mainly for surface courses)
STAC	Stone Asphalt Concrete (NL, type of HMA for base courses)
static load	load (of a vehicle or on an axle, tyre assembly or tyre) which is caused by gravity acting on the mass of the vehicle and its payload when the vehicle does not move
steering axle	axle on which the wheels can be steered for manoeuvring the vehicle
subbase	the layer between the roadbase and the subgrade
subgrade	natural soil underneath a pavement structure
super single tyre	originally a trademark for a specific type and brand of wide base single tyre, but often used to indicated any wide base single tyre
surface cracking	cracking in the bituminous material originating at the surface of the pavement, due to fatigue of the material by a great number of shear loadings of the pavement surface by the tyre, see Figure 4.13.
t	tonne = metric ton = 1000 kg. Formally, the tonne and kilogram are units of mass, not of weight (the force of gravity acting on that mass). However, they are often (as in this report) loosely used to indicate the weight in tf of kgf of the indicated mass.

tandem axle	a configuration of two axles, with less than 1.8 m spacing between the axles. (Often the suspension of a tandem axle is such that the load on the tandem axle is shared rather equally between the constituent axles.) The maximum load is dependent on axle spacing and suspension, and is different for motor vehicles or for trailers and semitrailers. (The EC also distinguishes a ‘bogie’, being two axles with shared suspension and less than 1.3 m spacing. In this report ‘tandem axles’ will be used loosely to include ‘bogies’, but not ‘double axles’.)
TCF	Tyre Configuration Factor
tf	tonne-force = 1000 kgf $\approx$ 9.81 kN. Often (as in this report), a tf is loosely taken to equal 10 kN.
thermal cracking,	cracking in the bituminous material due to tensile stresses caused by temperature changes
total width	in the regression formulae for the TCF, the ‘total width’ for single tyres equals the footprint width; the ‘total width’ for dual tyre assemblies equals the sum of the footprint widths of both tyres plus the width of the gap inbetween. (NB The ‘total width’ should not be confused with ‘tyre section width’).
towed axle	axle on which the wheels are neither driven, nor steered
tractor	leading, powered, part of a tractor-semitrailer combination (see Figure 4.74). A tractor is connected to the semitrailer by the fifth wheel and kingpin. (In this report, tractor is not used in its common meaning of vehicle for pulling agricultural machinery.)

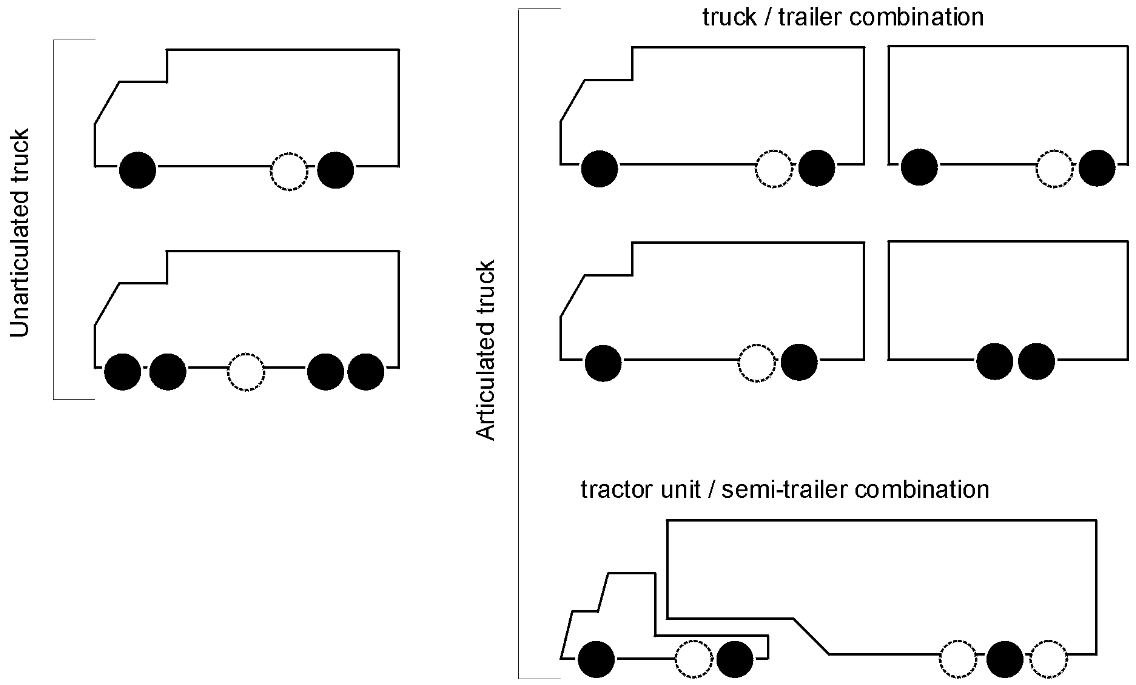


Figure 4.74 Types of heavy goods vehicles (Vos 1996)

trailer	an unpowered vehicle to be trailed by a truck. Unlike a semitrailer, a trailer is balanced on its own, and does not require the truck for vertical support (see Figure 4.74)
trailing axle	= towed axle
tri-axle	a configuration of three axles, with relatively short longitudinal distance between the axles. (Often the suspension of the tri-axle is such that the load on the tri-axle is shared rather equally between the constituent axles.)
TRL	Transport Research Laboratory (United Kingdom)
truck	heavy vehicle for transportation of goods. In a narrower sense often meant as an unarticulated vehicle, which can be followed by a trailer.
twin (tyre) assembly	= dual tyre
twin(ned) tyre(s)	= dual tyre
Tyre Configuration Factor	factor expressing the relative pavement wear of a tyre, as a function of its type, footprint width and inflation pressure, among other factors, see section 4.3.8.3
tyre load	load on one tyre
tyre width	in tyre size designations, this is the tyre section width (the width of the tyre at its widest point, see Figure 4.4) In the regression formulae for the TCF, the ‘width’ is the footprint width.
tyre	inflatable toroidal band around the rim of a wheel, made of rubber with reinforcing layers of steel or synthetic materials
UGM	Unbound Granular Material
underloading	operation of a tyre at a smaller load than recommended for the actual inflation pressure (i.e. relative overinflation)
UTAC	ultrathin asphalt concrete (surface course)
VTT	Technical Research Centre of Finland
wearing course	topmost structural layer (often of 0.02 – 0.05 m thickness) of a flexible or composite pavement
wheel load	load upon a single or dual tyre assembly (in t or kN) (The wheel load equals the tyre load for single tyres. The wheel load is the sum of the two tyre loads for dual tyres. Note that in vehicle engineering practice, ‘wheel’ is defined as “the metal part on which one tyre can be mounted. This is made of a rim, on which the tyre is mounted, and a disk, which is fitted on the vehicle hub.”)
wide base tyre	tyre which is not intended to be mounted in dual assembly, and with a load bearing capacity of the same order of magnitude as a dual tyre assembly

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