Publication no. 66

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Distress and damage factors for flexible pavements

Directorate of Public Roads
Norwegian Road Research Laboratory
Oslo, November 1992

Cover design:	Svein Aarset, Oslo
Cover photo design:	Arne Helland
Print:	GCS AS, Oslo 1992

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Preface

The Norwegian Public Roads Administration through the Norwegian Road Research Laboratory (NRRL) is currently carrying out a 4 year research programme focusing on various rehabilitation and construction techniques to ensure 10 tons allowable axle load with a minimum of load restrictions during the spring thaw periods. As a part of this programme a literature study has been conducted on the relative influence of factors related to traffic, pavement construction and climate on the damage to flexible road pavements.

The objective of this study was to present estimates of the relative damages for given ranges of vehicle and axle configurations, axle loads, tyre usage, road structures as well as climate based on results and findings reported in the international literature.

The liteature survey was conducted by ViaNova AS, a consulting engineering company, on a contract by the Norwegian Road Research Laboratory.

The project manager at NRRL was mr. Paul Senstad. Responsible for the project at ViaNova was mr. Ragnar Evensen.

Norwegian Road Research Laboratory, November 1992

1 Introduction

The Norwegian Public Road and Road Traffic Programme for 1994 - 97 includes a strategy for increasing the allowable axle loads to 10 tons for the majority of the National Roads before 1998 and all National Roads before the year 2000. The Norwegian Public Roads Administration is currently conducting a research programme titled "Better utilization of the bearing capacity of the roads" with the goal to reduce the current spring thaw load restrictions with a minimum of damage to the road pavements. This literature study is a part of this programme.

Based on the discussions in the literature, the study shall include estimates of the relative influence of different factors, related to the traffic, the pavement construction and the climate on the resulting damage and distress of flexible pavements. The range of the different loading factors to be discussed are listed in Chapter 3.

The objective of the study is to provide relative damage factors to be used in general discussions of the axle load policy in Norway.

Chapter 6 presents the conclusions of the literature study in tables of coefficients for the different factors. The use of the coefficients is demonstrated in Appendix 5 by calculations of the relative damage of a few selected vehicles with different loading conditions and configurations.

2 Load equivalency factors

In the AASHO Road Test (1) the damaging effects of different axle loads on a pavement were expressed in relative numbers based on a comparison with the damaging effect of a standard axle. The standard axle, or reference axle, was 8.2 tons (18 kips) single axle, dual tyres with bias tread. The Load Equivalency Factor, LEF, is normally expressed by equation (1):

$$LEF_x = \frac{N_{Ref}}{N_x} \qquad (1)$$

where N_x and N_{Ref} are the numbers of load repetitions in question and that of the reference axle respectively, causing the same amount of damage to the pavement.

With the introduction of the Load Equivalency Factor (LEF) it was possible to simplify a rather complex picture of axle load passages and to compare the effects of various loading conditions to the service life of the pavement. Different combinations of axle loads, axle and wheel configurations could then be expressed by a single number of Equivalent Single Axle Load passages, ESAL:

$$ESAL = \sum_{i=1}^{m} \ldots \sum_{j=1}^{n} LEF_{ij} \times N_{ij} \qquad (2)$$

where: LEF_{ij} = the Load Equivalency Factor of axle load j and axle configuration i
N_{ij} = the number of passages of an axle with axle load j and axle configuration i

Unfortunately, the Load Equivalency Factor does not depend on the axle loads only. Other factors, such as the type of damage criterion in question, the pavement structure and the amount of damage accepted, all have an influence on the LEF's.

In the AASHO Road Test, equivalency factors were developed using the reduction in the Present Serviceability Index, PSI, as an expression of the functional damage to the road.

The Present Serviceability Index expresses the functional performance of a pavement, ranging from 5.0 for a pavement in excellent condition, to 0.5 for a pavement unsuitable for traffic. The lowest acceptabe PSI value for a road subjected to normal traffic is usually considered to be 1.5 or 2.0. By regression the PSI was found to be a function of the longitudinal roughness of the surface, the average rut depth, and the area of cracking and patching. The PSI is discussed more in detail in Appendix 2.

Although the PSI is dominated by the roughness of the pavement surface, it is intended to express the combined functionalities of a road pavement. The PSI is not put forward with the intention to reflect or to express the structural damage of the road.

The AASHO Road Test presented Load Equivalency Factors in tables depending on the axle load, the pavement structure (expressed by a Structural Number) and the minimum acceptable PSI, with separate tables for single axles and tandem axles. These tables are later expanded to include triple axles.

The Structural Number of the pavement and the minimum acceptable PSI have a relatively small influence on the LEF's, and the equivalency factors are often simplified as indicated in equation (3):

$$LEF_x = \frac{N_{Ref}}{N_x} = \left(\frac{P_x}{P_{Ref}}\right)^{\gamma} \tag{3}$$

where the exponent γ is usually accepted to be 4.0. For this reason the equation above is called "the Fourth Power Law".

In order to take into account different axle configurations, wheel and suspension types, the OECD (58) presented in 1983 an expansion of the Fourth Power Law, equation (3) into equation (4) :

$$LEF = \left(k_1 \times k_2 \times k_3 \times \frac{P}{P_0}\right)^{\gamma} \tag{4}$$

where: k_1 represents the axle configuration,
k_2 represents the wheel type
k_3 represents the suspension type.

The OECD concluded that one could with an acceptable accuracy assume the factors to be constants and suggested the values listed in Table 1.

γ	Exponent	4.0
k_1	Single axles	1.00
	Tandem axles	0.60
	Triple axles	0.45
k_2	Dual tyre	1.00
	Wide base single tyre	1.20
	Normal single tyre	1.30
k_3	Traditional suspension	1.00
	Improved suspension	0.95

Table 1: Coefficients for LEF estimated from tensile strains.

Deacon (29) has later suggested a further expansion of the OECD equation to:

$$LEF = \left(k_{at} \times k_{as} \times k_{wt} \times k_{tp} \times k_{st} \times \frac{P}{18}\right)^{\gamma} \tag{5}$$

where
k_{at} : expresses the effect of axle type
k_{as} : expresses the effect of axle spacing
k_{wt} : expresses the effect of wheel type
k_{tp} : expresses the effect of tyre pressure
k_{st} : expresses the effect of suspension type
P : the load on one single axle (kips)

The equations (4) and (5) have the advantage of relating the influence of the different factors directly to the axle loads.

As an example: a coefficient k equal to 1.20 has the same influence on the LEF as a 20 percent increase of the axle load. Equation (5) implies also that the reference axle is loaded to 8.2 tons (18 kips).

Many investigators, however, express the relative influence of heavy traffic loads on the distress of flexible pavements by a slightly different expression:

$$LEF = k_{at} \times k_{wt} \times k_{ld} \times k_{tp} \times \left(\frac{P}{P_0}\right)^{\gamma} \tag{6}$$

where k_{at} : expresses the effect of axle type, including the axle spacing

k_{wt} : expresses the effect of wheel type

k_{ld} : expresses the effect of uneven load distribution on dual tyres

k_{tp} : expresses the effect of tyre inflation pressure

P : the load on one single axle

P_0 : the reference load on one single axle

In this expression it is not quite as simple to relate the different coefficients to the effect on distress by a change in the axle load. It has, however, other advantages. The main advantage is the direct relationship between the coefficients and the number of load repetitions. For a tandem axle with large axle spacing, the axles may be considered as two independent single axles, having a combined effect equal a coefficient k_{at} = 2.0. Similarily, for a triple axle with large spacing, the coefficient will be 3.0 as it can be regarded as three independent single axles. This requires, however, that the axle loads are expressed as loads per axle.

Radial tyres will normally require higher tyre inflation pressures than bias tread tyres. The wheel type will in general have an influence on the recommended tyre pressure, as has the axle load. Several investigators find it important to express realistic relationships between the different load equivalency factors, while others discuss the factors as independent variables. The differences between these two approaches have to be acknowledged when comparing the results from different investigations. In this study all discussion on the effects of the influence of the traffic factors are considered independent.

The influence of traffic loads and their various components on the relative damage of road pavements are in this literature study based on equation (6) above. The different factors are treated as independent variables, and axle loads are expressed as load per axle.

The effects of vehicle suspension and traffic speed are not included in the objective of this study. The influence of variations in the tyre contact pressure over the tyre contact area is neither included in the objective of the study, but is briefly discussed for a pavement with a thin surface layer on a weak base material.

3 The damaging factors

The objective of this literature study is to discuss and present the relative influence of a number of different loading factors related to heavy vehicles on the damaging effects on flexible pavements. These loading factors are defined and expressed in Tables 2, 3 and 4. The objective of the discussion and the results are to provide relative numbers to be used in general discussions of various future axle load policies in Norway.

The different factors are to be considered independent. It is not within the scope of this study to provide or discuss the composition of the heavy traffic on Norwegian roads, neither the possible dependancy between the different loading factors nor damaging factors. Also, the discussion shall not include the dynamic effects of vehicles in motion nor the influence of vehicle suspension systems.

3.1 Single axles

For single axles the damaging factors of the following loading factors are to be examined:

Axle loads, tons	4	6	8	10	12	14
Tyre inflation pressure, kPa:	600		800		1000	
Tyre configuration:	Single tyre			Dual tyre		
Load distribution between tyres:	50/50			25/75		

Table 2: Single axle loading factors.

The discussion of the influence of single tyres vs. dual tyres shall include the influence of normal single tyres and wide base singles as a minimum.

3.2 Tandem axles

For tandem axles the discussion shall include the same loading factors as for single axles. The range of axle loads expressed as the total load on the tandem axle configuration is higher than for single axles, see Table 3 below.

For tandem axles, the discussion shall include the effects of varying the axle spacing. The influence of possible uneven distribution of loads between the axles is also to be discussed.

Axle loads, tons:	6	10	14	18	22	26
Load per axle, tons:	3	5	7	9	11	13
Axle spacing, m	1.00	1.20	1.40	1.60	1.80	
Tyre inflation pressure:	600 kPa		800 kPa		1000 kPa	
Distribution of loads between the axles:	50/50			25/75		

Table 3: Tandem axle loading factors.

3.3 Triple axles

For triple axle configurations the factors to be discussed are very much the same as for tandem axles. For the distribution of loads between the different axles in this axle group, the influence to be discussed is not related to a specific distribution.

Axle loads, tons:	12	18	24	30	36
Load per axle, tons:	4	6	8	10	12
Axle spacing, m:	1.20	1.40	1.60	1.80	
Tyre inflation pressure	600 kPa		800 kPa		1000 kPa
Distribution of loads between the axles:	Open for discussion				

Table 4: Triple axle loading factors.

3.4 Pavement structures

The discussion shall focus on typical flexible road structures in use in Norway as well as Norwegian climate. These structures are in this report expressed by two pavement structures; "normal" structure and a structure with a weak base layer.

According to "the Norwegian Pavement Design Manual" (Vegnormalene Håndbok 018) a typical pavement structure may consist of:

Surface course:	Bituminous material	5 cm
Base material:	Crushed gravel	15 cm
subbase material:	Gravel, partly crushed	45 cm

This pavement structure will comply with the strength requirements for a road with an AADT of 2000, 10 percentage heavy traffic, a design life period of 20 years and a frost susceptible subgrade consisting of clay.

This road structure will have a Structural Number of approximately 3.6 according to AASHTO.

A traffic volume of 2000 in AADT is in the upper range of the public roads in Norway; approximately 75 percentage of the National Road network have an AADT less than 2000, see Table 5.

Road network	Trunk Roads	Other National Roads	County Roads
Average traffic volume	1700	800	200
Traffic volume at the 80 percentile of road network	5000	1900	600

Table 5: AADT on the Public Roads in Norway

The literature on the relative influence of heavy vehicles on the damage of flexible pavements include little information related to road structures with weak base materials. In general, according to the AASHO Road Test (1) (3) the equivalency factors of the different loading factors show relatively low sensitivity to the pavement stength. The main differences between a "normal" structure compared with that of a structure consisting of a thin asphalt surface on a weak base, are most likely to be:

* Tandem and triple axles on a "normal" structure can to a much greater extent be regarded as single axles as the interactions between the axles are negligible even for axle spacing as close as 1.0 m.

* The influence of tyre inflation pressure on the damage is greater for pavements where the critical strains are located at shallow depths beneath the surface. Comparing with most of the pavements presented in the literature, both the "normal" and the weak base structures in this study have thin asphalt courses. However, for structures with a "weak base" the critical strains will be directly under the thin asphalt course.

* Although not included in the objective of this study, the influence of uneven distribution of the contact pressure can be expected to be greater for "weak base structures" than on "normal" structures. The maximum contact pressure should be considered.

3.5 The climate

In this study the influence of the climate is considered to be covered by the properties of the materials within the pavement structure. The pavement structure with a "weak base", may be a structure with generally weak base materials. However, more often such a structure will represent a structure with reduction in the bearing capacity of the base course during the spring thaw periods.

3.6 The reference axle

In the literature, a discussion of the relative influence of the different factors in flexible road pavement damage may be based on different references. This is important to notice when the various conclusions are compared. The AASHO Road Test was based on a single axle dual tyre of 8.2 tons (18 kips) having a tyre inflation pressure in the order of 528 kPa (75 psi) (1). Results observed from the Virttaa field test are for example based on a single axle of 10 tons (22 kips), dual radial tyres (12 R 22.5) with an inflation pressure of 700 kPa (2).

In this literature study the reference load is a 10 tons (22 kips) single axle dual tyre 12 R 22.5 with an inflation pressure of 800 kPa. This load is for the reference axle assumed evenly distributed on both tyres in the dual tyre configuration.

4 Vehicle related factors

The dominant vehicle factor on pavement damage will in most cases be the axle load. In a discussion of vehicle related factors and their combined relative influence on the damage of pavement structures, it would therefore be natural to start with a discussion of the influences of the axle loads.

In this study the axle load and the tyre pressure are to be considered as independent variables. In several investigations the tyre inflation pressure is adjusted to the axle load according to recommendations from the tyre manufacturers; thus the influence of the tyre inflation pressure is included in the influence of the axle load. In these investigations the conclusions regarding the influence of the axle loads will have to take into account the estimated influence of the tyre inflation pressure itself. It is therefore, in this study, natural to start the discussion of the vehicle related factors with the influence of the tyre inflation pressure.

A complete discussion of the different factors and their influences on the relative damage of road pavements should include a discussion based on the following damage models:

* Asphalt fatigue cracking.
* Pavement rutting and permanent deformation of asphalt.
* Pavement rutting and shear deformations of the subgrade materials.
* Surface roughness.

In this study it has not been possible to include nor to present a complete and separate discussion of all the factors related to the damage models above. Several investigations do not relate damaging factors to accepted and known damage models, others base the discussions on a combination of damage models.

4.1 The tyre inflation pressure

In all discussions on the distress of road pavements, the influence of the tyre inflation pressure is closely related to a discussion on the shape and the size of the contact area, as well as the distribution of the contact pressure between the wheel and the pavement, involving both the type and the dimensions of the tyre (76). The objective of this study is to focus on the possible damaging effects of the tyre inflation pressure.

The tyre inflation pressure is normally measured at ambient temperatures and reported as the cold inflation pressure. Internal friction in a rolling tyre on the pavement will cause a temperature increase, which increases the inflation pressure. The operational inflation pressure is in the order of 70 - 100 kPa higher than the cold pressure (93) (97).

The majority of computer programs for estimating the primary response from traffic loads on flexible pavements simplify the tyre contact area to a circular area with a uniform distributed contact pressure. Contact pressure equal to the inflation pressure is often assumed.

The real contact area is normally more rectangular than circular in shape (19) (76). The contact pressure distributions for radial tyres are usually different from those of the bias tread tyres. In addition the contact pressure varies depending on the inflation pressure and the make of the tyre. The maximum contact pressure may be as high as twice the inflating pressure (80).

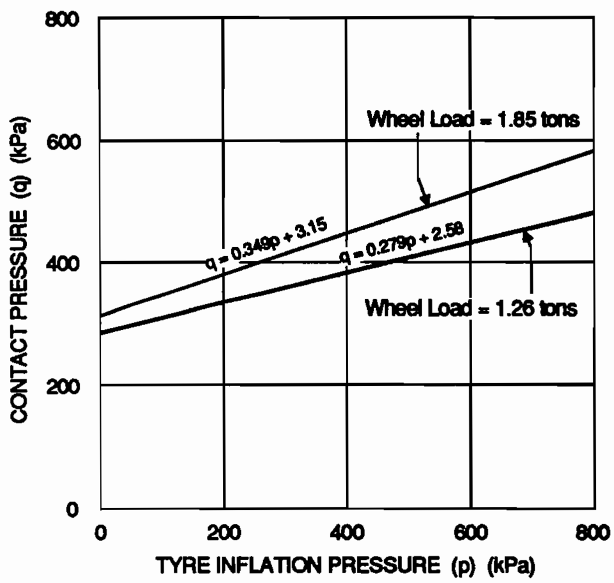


Figure 1: Tyre inflation pressure (p) and contact pressure (q) for constant values of wheel load, Ref. (92).

Van Vuuren (92) suggested for bias tread tyres a linear relationship between the inflation pressure and the contact pressure as shown in Figure 1. The upper line represents a wheel load of 1.85 tons, which correspond to a single axle of 7.4 tons. This axle load is in the lower part of the axle load factors to be discussed in this study.

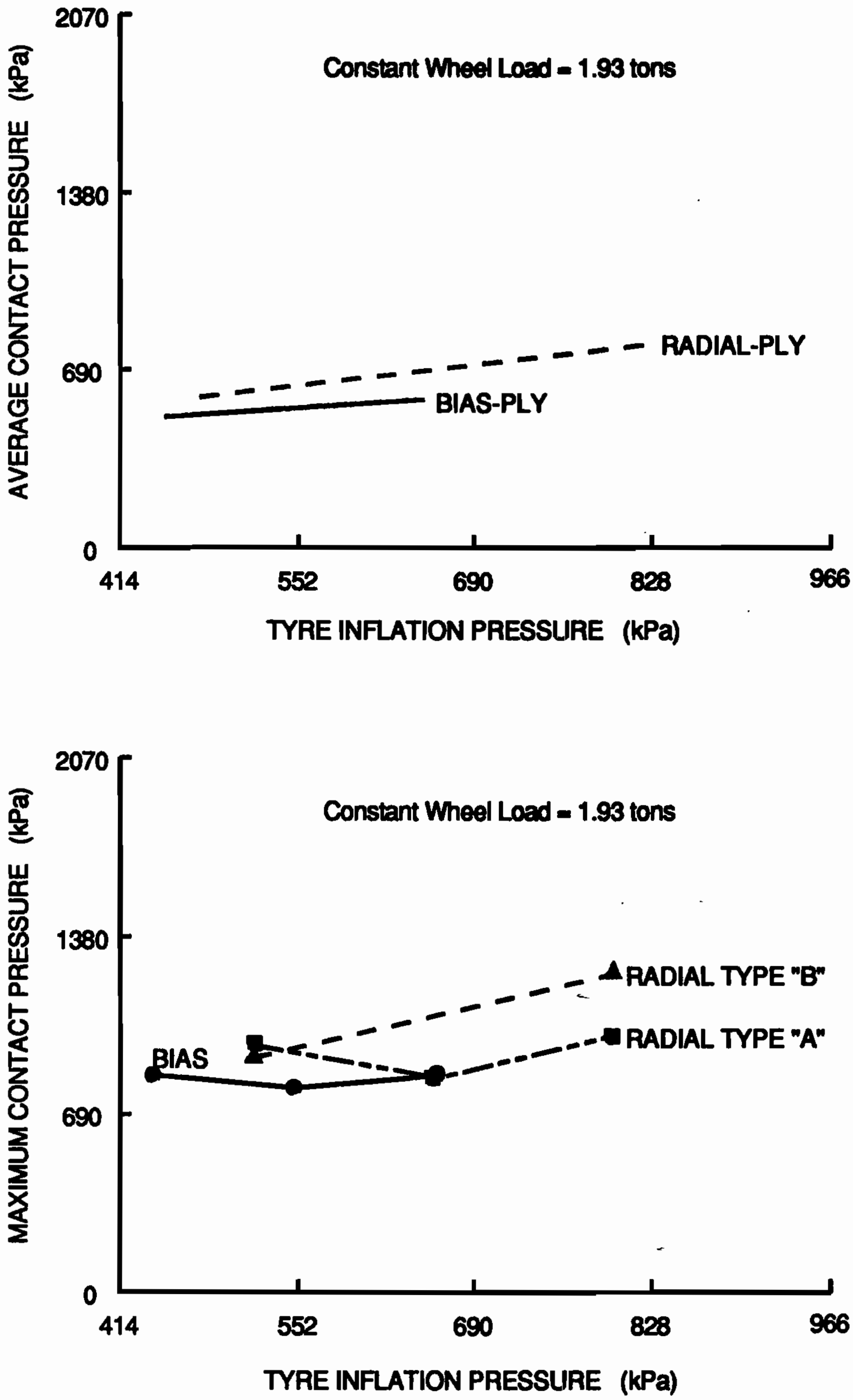


Figure 2: Average and maximum contact pressure versus inflation pressure, Ref. (94).

In Figure 2 the relationship between the average contact pressure and the maximum contact pressure recently reported by P. Yap (94) is compared with results for a single wheel load of 1.85 tons reported by van Vuuren. The results are in acceptable agreement. For discussions given later in this report the results from P. Yap are used when inflation pressures are converted to average contact pressures:

$$\textit{Bias tread:}\quad q = 431 + 0{,}163 \times p \qquad (7)$$

$$\textit{Radial tread:}\quad q = 348 + 0{,}475 \times p \qquad (8)$$

where p = tyre inflation pressure (kPa)
q = average contact pressure (kPa)

4.1.1 Fatigue cracking

For fatigue cracking of flexible pavements the influence of the tyre pressure is considered for thin pavements only (80). Figure 3 presents the tensile strain as a function of asphalt thickness, axle load and tyre pressure. For total asphalt thicknesses of 15 cm (6 inches) or greater the influence of tyre pressure on the tensile strain within the bottom of the asphaltic layer can be neglected. For asphalt thickness of 5 - 10 cm (2 - 4 inches) the fatigue potential is significant.

A simple regression analysis of the data presented in Figure 3 will for an asphalt layer thickness of 5 cm result in tensile strains at the bottom of the asphalt layer as presented in Table 6. The fatigue damage model of Finn et al. may be used for calculations of load applications to "failure". Assuming an E-modulus of 2800 MPa (400.000 psi) and a reference tyre inflation pressure of 800 kPa, the relative damage factors for 600 kPa and 1000 kPa tyre inflation pressures will be as reported in Table 6. (The fatigue damage model of Finn et al. is discussed in Appendix 2.)

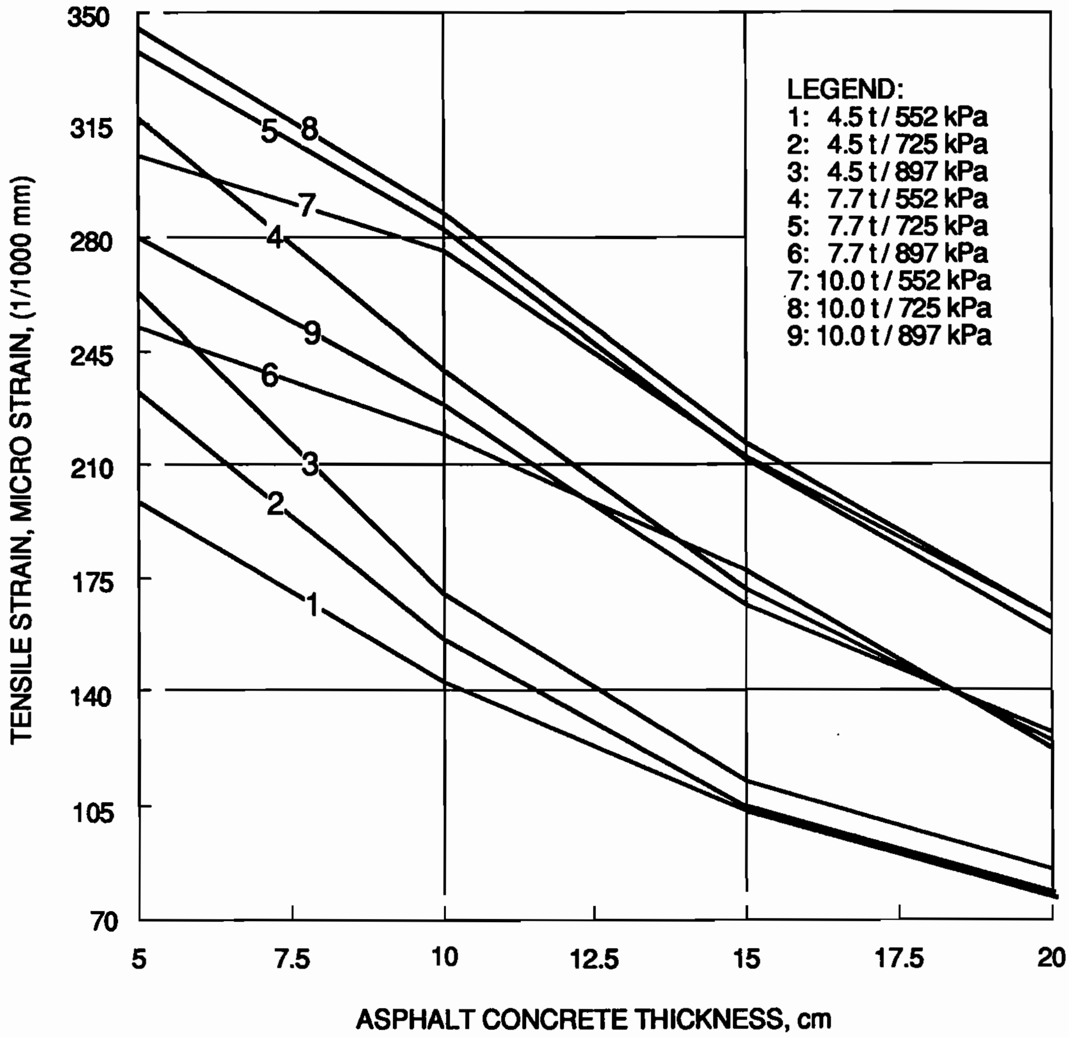


Figure 3: Effects of tyre inflation pressure and wheel load on the tensile strain at the bottom of the asphalt layer, dual radial tyres, Ref. (80)

For an axle load of 7.7 tons the damaging factors in Table 6 indicate a relative fatigue damage (for 5 cm asphalt on a granular base course) in the order of 2.25 for a 67 percentage increase in the tyre inflation pressure.

This is not very different from what is reported by the FHWA Project 1-25 (34): a coefficient of 3.0 for a 60 percent increase in tyre inflation pressure and a 7.5 cm asphalt thickness. For wide base single tyre the same investigation reports a coefficient greater than 9 as the damaging factor for the same increase in tyre inflation pressure.

Axle load tons	Tyre pressure	tensile strain microstr.	Loads to "failure" millions	Relative damaging factor
4.5	600 kPa	205	7.8	0.59
	800 kPa	240	4.6	1.00
	1000 kPa	275	3.0	1.53
7.7	600 kPa	260	3.6	0.67
	800 kPa	295	2.4	1.00
	1000 kPa	330	1.6	1.50
10	600 kPa	310	2.0	0.80
	800 kPa	332	1.6	1.00
	1000 kPa	350	1.3	1.23

Table 6: Tyre inflation pressure coefficients, fatigue, calculated from tensile strains, asphalt thickness 5 cm.

Table 6 indicates also an interaction between the tyre inflation pressure and the axle load: the influence of the inflation pressure is greatest at low axle loads.

The relative damaging factor in Table 6 is the same as the coefficent k_{tp} in Equation 6. It expresses the influence of the tyre inflation pressure only. Table 6 is not to be used in a discussion of the influence of the axle loads.

Southgate and Deen (81) suggest the following regression function (Equation 9) for an adjustment factor for the influence of the tyre contact pressure:

$$Log\ (Adj.fact.) = A + B \times Log(q) + C \times (Log(q))^2 \qquad (9)$$

where Adj.fact = Adjustment factor for tyre pressure
q = Tyre contact pressure (psi)
A, B and C = Regression constants

The regression constants A, B and C were based on an axle load of 8.2 tons and a tyre inflation pressure of 528 kPa (75 psi). For an asphalt thickness of 7.5 cm the regression constants reported by Southgate and Deen (81) will give relative damage factors as shown in Table 7. In this table the reference tyre inflation pressure is 800 kPa.

Tyre inflation pressure	600 kPa	800 kPa	1000 kPa
Single tyre, bias tread	0.78	1.00	1.26
Single tyre, radial tread	0.59	1.00	1.56
Dual tyre, bias tread	0.87	1.00	1.15
Dual tyre, radial tread	0.72	1.00	1.35

Table 7: Tyre inflation pressure coefficients, fatigue, Southgate.

The tyre inflation pressure coefficients in Tables 6 and 7 are based on calculations from estimated tyre contact pressures. In these calculations the tyre inflation pressure is increased by 15 percent and 10 percent for bias and radial tread respectively, as an estimate of the difference between cold and operational tyre inflation pressures.

Analysis based on finite element methods for actual footprint loading (97) concluded that conventional analyses overestimate the tensile strain at the bottom of the asphalt surface layer. This will subsequently overestimate the influence on fatigue cracking.

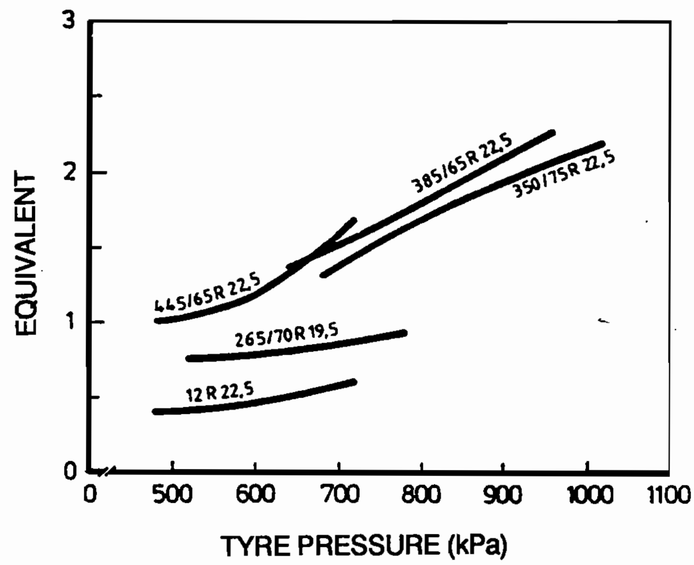


Figure 4: The Load Equivalency Factor as a function of tyre pressure, axle load 84 kN, thickness of the bituminous layer 80 mm, Ref. (2) (42).

The Virttaa Test Road (2) (42) based the discussion of equivalency factors on measured tensile strains at different inflation pressures, combining the results with the Shell damage function. (The Shell damage function is reported in Appendix 2). The results for 8.0 cm thick asphalt surface course on a 15 cm thick granular base course and a subbase 40 cm thick, are shown in Figure 4 for 8.5 tons single axle load. Adjusting to a reference tyre inflation pressure of 800 kPa, the conclusions of the Virttaa study can be summarized as in Table 8:

Tyre Inflation pressure	600 kPa	800 kPa	1000 kPa
Dual radial tyres	0.50	1.00	N.A.
Wide base tyres	0.52	1.00	1.31

Table 8: Tyre inflation pressure coefficients, fatigue, Virttaa.

For the same inflation pressure and the same single axle load the wide base tyres have equivalency factors twice that of a conventional dual tyre axle (2) (42). The relative influence of the tyre pressure, however, seems to be nearly the same for both types of tyres.

The Virttaa results and the results from Southgate and Deen are related to an asphalt course thicker than what is assumed representative for roads in Norway.

The damaging factors for 1000 kPa tyre inflation pressure, based upon measured tensile strains at the Virttaa road test, are less than the corresponding factors reported by Southgate and Deen (81). The results from Southgate and Deen are in agreement with those from the NCHRP Project 20-7 (80). On the other hand, the coefficients for 600 kPa tyre inflation pressure indicate a greater influence for the tyre inflation pressure according to the Virttaa test than what is reported by Southgate and Deen and in Project 20-7 (80).

When fatigue cracking is assumed to be critical for the damage of a flexible pavement, it is suggested that the discussions are based on the damaging factors listed in Table 7. Assuming the radial tread are the most widely used tyre type, the coefficients for that type are suggested when the influence of tyre inflation pressure are discussed in general terms.

When the influence of tyre inflation pressure is discussed in more detail, it is important not to ignore the influence of the tyre type and the interaction between the axle load and the tyre inflation pressure.

It is also improtant to know that the damaging factors of the tyre inflation pressure listed in Table 7 are based on results from large scale field tests and analyses where the inflation pressure was altered using the same type of tyre.

The influence of the tyre inflation pressure may be different when based on results from other investigations having examined various tyre constructions for different inflation pressures. In these investigations, however, the influence of the inflation pressure is extremely difficult to separate from the influence of the various tyre constructions used.

4.1.2 Rutting of asphalt materials

Rutting of asphalt materials is in Norway a problem which has to be discussed slightly different from that in other countries. For an average road there is generally very few problems with rutting of the asphalt because of the small asphalt thicknesses. For roads with AADT greater than 3000 the wear of the pavement due to studded tyres is regarded as the major factor controlling the resurfacing sequences. Traditionally, a high wear resistant asphalt surface layer will have a high bitumen content and a low volume of air voids. For roads where the wear from studded tyres is the dominant factor for resurfacing, the optimum composition may accept a slightly unstable mix.

Rutting due to permanent shear deformations within asphalt materials, is a significant problem for areas with slow moving or standing traffic. It is also considered a problem for surface courses immediately after placement and compaction when the pavement is subjected to traffic when the surface layer is stoll at an elevated temperature. On roads with heavy traffic, the traffic is thus normally not allowed within the first 1.5 hours after placement of a new asphalt surface layer.

FHWA Project 1-25 (34) assumes a linear relationship between the total loads and the rutting. An increase of tyre pressure is assumed to provide greater rutting as the load is applied on a smaller area. T. D. Gillespie et al. (34) estimate the effect of the inflation pressure as shown in Figure 5.

From Figure 5 the following coefficients for the influence of the tyre inflation pressure on asphalt rutting can be extracted:

Tyre inflation pressure	600 kPa	800 kPa	1000 kPa
Conventional dual radial tyre	0.97	1.00	1.03
Wide base single tyre	0.90	1.00	1.10

Table 9: Tyre inflation pressure coefficients, rutting.

The damaging factors for dual radial tyre are related to an axle load of 9.1 tons, while the factors for the wide base sinlgle tyre are related to an axle load of 7.3 tons.

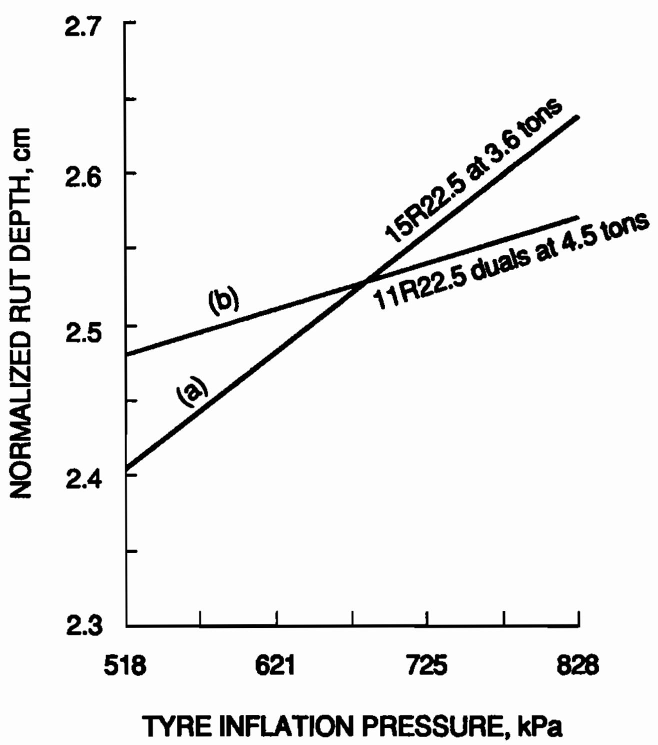


Figure 5: Rut depth versus tyre inflation pressure for wide base single tyres (a) and dual tyres (b), Ref. (34).

Several other authors base their discussions on rutting using a distress model with a linear relationship between the rut increase and the square root of the number of passages:

$$R = a + b \times \sqrt{N} \tag{10}$$

where the regression constant "b" expresses the rate of rutting. In a laboratory test facility Eisenmann and Hilmer (31) studied the effects of different wheel types and inflation pressures on the contact pressures and rutting of asphalt in pavements.

Figure 6 reports the findings (31) by showing the relationship between the average contact pressure and the regression coeffisient "b", which can be considered as a good expression for the potential rate of rutting.

Using equations 7 and 8 for the relationship between the inflation pressure and the average contact pressure, the coefficients in Table 10 for the relative influence on the rate of rutting of asphalt can be drawn.

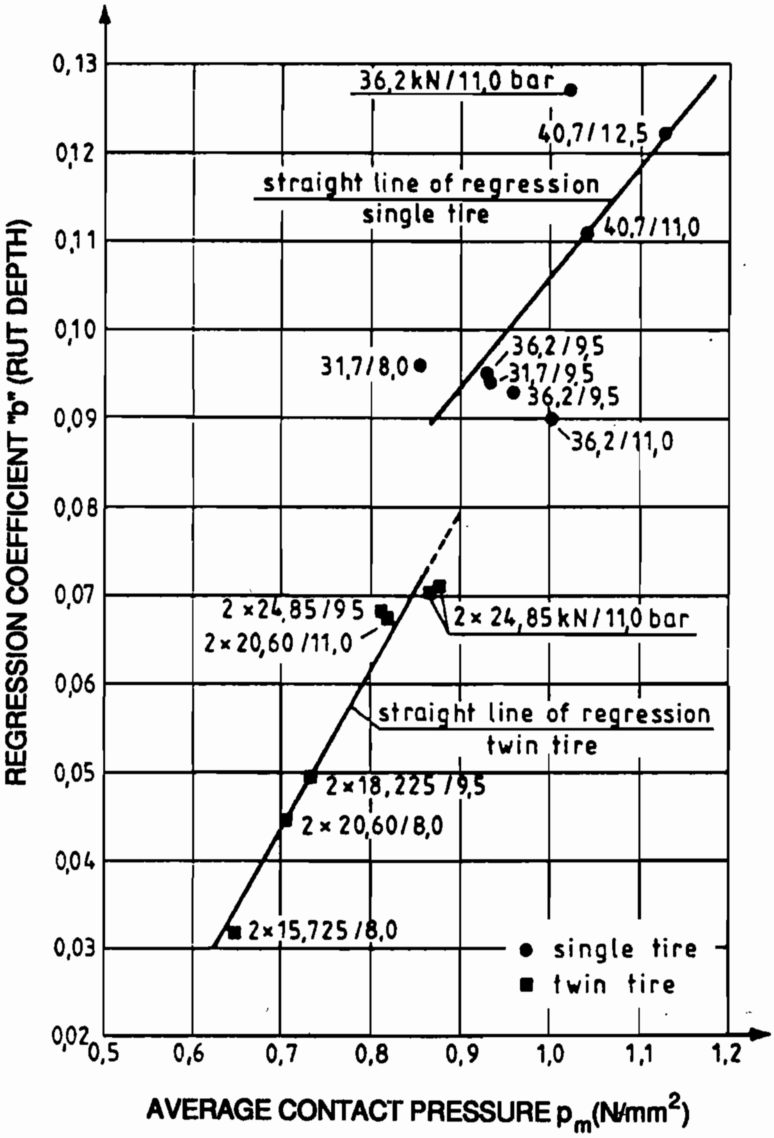


Figure 6: The coefficient b in Equation 10 expressing the rate of rutting at different tyre/pavement contact pressures, Ref. (31).

Tyre inflation pressure	600 kPa	800 kPa	1000 kPa
Bias tread tyre	0.77	1.00	1.32
Radial tread tyre	0.67	1.00	1.39

Table 10: Tyre inflation pressure coefficient, rutting.

The difference in damaging factors between bias tread and radial tread tyres is the result of a higher contact pressure for wide base single tyres. According to Figure 6 the rate of rutting for single wide base tyres is 50 percent higher than for dual tyres. The relative influence from the inflation pressure, however, are nearly the same.

When rutting of asphalt is considered to be a problem, it is recommended that the relative influence with regard to tyre inflation pressure can be expressed by the damaging factors given in Table 10.

4.1.3 Rutting and roughness, shear deformations in unbound materials

In many investigations a "normal" pavement structure has asphalt course thicknesses in the range 10 - 20 cm. For these pavements the tyre inflation pressure will have an almost negligible influence on the vertical subgrade strain (50). This conclusion is in agreement with the findings of Marshek et al. (54), where the critical vertical strains in the subgrade were found to be the same for inflation pressures 528 kPa (75 psi) and 774 kPa (110 psi) for asphalt course thicknesses down to 5 cm. For smaller thicknesses the influence of inflation pressure was still rather small. Eiesenmann and Hilmer (31), however, concluded that the influence of inflation pressure could on a warm summer day reach down to a depth of 10 - 15 cm below the pavement surface.

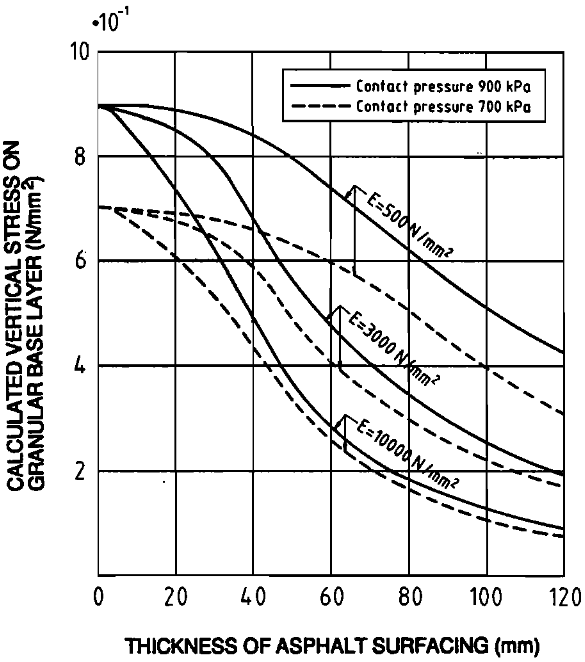


Figure 7: Calculated vertical stress on granular base layer for contact pressures of 700 and 900 kPa, Ref. (57).

This conclusion is confirmed by Noss (57) as indicated in Figure 7. E-moduli of 10000 MPa, 3000 MPa and 500 MPa correspond roughly to temperatures of 5°C, 25°C and 40°C respectively. From Figure 7 it can be read that the maximum vertical stress in a granular base course underlying a 5.0 cm asphalt surface course will increase approximately 10, 30 and 30 percent respectively for the three different asphalt moduli. An increase of this magnitude will by most damage prediction models cause a considerable reduction in service life of a pavement.

According to equations 7 and 8, however, an increase from 700 to 900 kPa in average contact pressure will correspond to rather unrealistic increases in the tyre inflation pressure. Using equations 7 and 8, an increase in tyre contact pressures from 700 to 900 kPa will require an increase in tyre inflation pressures of 75 percent for bias tyres, and of 57 percent for radial tyres.

According to the relationship between the tyre inflation pressure and the average contact pressure for radial tyres, as expressed by the equation (8), an increase in the inflation pressure from 800 to 1000 kPa, will increase the vertical compressive strain at the top of the granular base course by 13 percent. The Asphalt Institute damage model, which is reported in Appendix 2, indicate a damage factor in the order of 1.49 for 1000 kPa and 0.67 for 600 kPa with respect to shear deformations in the subgrade materials.

4.2 Single tyres

A large number of investigations conclude that single tyres are more damaging than dual tyres. The OECD suggested in 1983 (58) the coefficients 2.9 for normal single tyres and 2.1 for wide base single tyres. In the OECD report no distinctions were made between the damage of rutting and of fatigue cracking.

Relative to a dual tyre 11 R 22,5 Gillespie et al. (34) propose equivalency factors as listed in Table 11. The Load Equivalency Factors in Reference 34 are corrected to a reference axle load of 8.2 tons.

The difference between the coefficients for fatigue cracking and for rutting is relatively small for 10 cm asphalt thickness. For fatigue cracking of 5 cm asphalt, however, the coefficients for wide base tyres are less than 1.0, indicating that the asphalt acts more like a flexible membrane. Other investigations (40) confirm this conclusion.

Tyre type	11 R 22,5	15 R 22,5	18 R 22,5
Nominal tread width, inches	**8**	**11**	**14**
Fatigue 5 cm asphalt	3.33	0.97	0.44
Fatigue 10 cm asphalt	3.32	1.81	1.22
Rutting 5 cm asphalt	2.78	1.67	1.18
Rutting 10 cm asphalt	2.80	1.68	1.20

Table 11: Coefficients for single tyres, Gillespie.

Based on a discussion of several investigations, Deacon (29) propose the coefficients listed in Table 12 as a function of the tyre width and the axle load. In Deacons proposal there were no distinctions between equivalency factors related to fatigue cracking and to rutting.

	Tyre width, inches				
Axle load tons	**10**	**12**	**14**	**16**	**18**
5.5	5.23	3.78	2.82	2.12	1.68
8.2	3.99	2.91	2.19	1.68	1.25

Table 12: Single tyre coefficients, Deacon.

Unfortunately, Table 11 and 12 are difficult to compare as the results from Deacon (29) are related to axle loads while the Gillespie results (34) are related to the asphalt course thickness. Assuming that "tyre width" is to be read as the nominal section width, the coefficients by Deacon for 8.2 tons axle load, correspond reasonably well with those of Gillespie for pavement rutting.

In a recent field test Akram et al. (6) investigated the damage effects of wide base tyre 425/65 R 22.5 inflated to 915 kPa, relative to dual tyres 11 R 22.5 inflated to 845 kPa. For a 4 cm thick asphalt surface on a 25 cm crushed limestone base, the wide base tyre was 2.8 times more damaging than the dual tyres. For a 18 cm asphalt surface on a 36 cm base course, the ratio was 2.5. These conclusions are based on the Asphalt Institute damage model for subgrade vertical strain.

Sebaaly (75) reports a field investigation of the damaging effects of wide base tyres based on estimated fatigue cracking:

Tyre type	11 R 22.5 dual reference	245/75 R 22.5 dual	385/65 R 22.5 single	425/65 R 22.5 single
15 cm asphalt	1.0	1.0	1.7	1.5
25 cm asphalt	1.0	1.3	1.5	1.5

Table 13: Equivalency factors, asphalt fatigue.

The results correspond reasonably well with those of Gillespie (34). The low equivalency coefficient for the dual 245/75 R 22.5 is explained by the influence of the small tyre spacing of these dual tyres on the location of the critical strains. It is important to note that the investigation of Sebaaly is based on asphalt thicknesses of 15 cm on a 20 cm granular base course.

Using an axle load of 8.4 tons the Virttaa field test (2) (41) (42) gave the following equivalency coefficients after correction for the differences in tyre inflation pressures:

Tyre type	Optimal inflation pressure	Equal tyre pressure 600 kPa
12 R 22.5, reference	1.0	1.0
350/75 R 22.5	3.96	2.06
385/65 R 22.5	3.91	2.03
445/65 R 22.5	2.52	2.52

Table 14: Equivalency coefficients asphalt fatigue,Virttaa.

The equivalency coefficients of single tyres are higher in the Virttaa test than the other investigations reported. The results also indicate that the tyre 445/65 R 22.5 has a larger coefficient than the 385/65 and the 350/75 tyres, an influence of the tyre width which is different than what is reported by other investigators.

By comparing the damaging factors reported in Tables 11 - 14, the factors proposed by Deacon, see Table 12 above, can be accepted as a reasonable average for the damaging factors for single tyres relative to the damaging potential of a dual tyre 12 R 22.5. The coefficients can be considered valid for both fatigue cracking and rutting, when fatigue of thin asphalt courses on granular materials (thicknesses up to 5 cm) is excluded.

4.3 Uneven loads on tyres

A great majority of investigations conclude that single tyres, normal or wide base, are considerably more damaging to pavements than dual tyres.

The OECD report of 1983 (58) suggested a damaging factor for normal type single tyres of $1.30^4 = 2.86$. Deacon (29) proposes a factor varying from 3.99 to 1.25 for 8.2 tons single axles, single tyre widths varying from 250 mm (10 inches) to 450 mm (18 inches).

In these discussions it is assumed that the loads on dual tyres are evenly distributed on both tyres. There are, however, several factors which may cause an uneven distribution of the wheel loads on the dual tyres.

* Differences in the inflation pressures of the dual tyres.
* Uneven wear of the dual tyres.
* Transverse position of the tyres relative to the ruts in the road surface.

For roads where the studded tyre wear is considerable, there are reasons to believe that the applied loads from the dual tyres may be far from evenly distributed.

For a 10 tons axle with dual tyres, the load per tyre will be 2.5 tons. With a 25/75 load distribution among a set of dual tyres one tyre will carry 3.75 tons. This will cause an increase in the average contact pressure in the order of 150 kPa (94).

The Virttaa test field (2) is one of the very few investigations carried out to examine the influence of uneven load distribution on dual wheels. In addition to vary the inflation pressure, the effect of uneven load distribution of the tyres were investigated by inflating one of the dual tyres to 500 kPa keeping the other tyre inflated at 1000 kPa.

The influence of the uneven distribution is presented in Figure 8 for both 8 cm and 15 cm asphalt course thicknesses. The influence is expressed by equivaleny factors from measured tensile strains at the bottom of the asphalt layer, combined with the Shell's damage functions. From Figure 8 it can be concluded that the uneven pressure distribution increases the equivalency factors in the order of 80 percent for the thin pavement and 60 percent for the thick pavement.

Based on analytical analysis using the computer program BISAR, Zahnmesser (96) has investigated the influence on uneven load distribution between dual tyres on the primary responses of a pavement. In Figure 9 the distribution of shear stresses are reported for a load distribution of 50/50 and 60/40. The analysis are based on an axle load of 10 tons and a contact pressure of 600kPa for the 50/50 distribution and 710/500 kPa for the 60/40 distribution. The influence of the wheel load on the contact pressure is higher than assumed from equation (8). However, Zahnmesser (96) generally assumes a higher influence of the inflation pressure on the contact pressure.

From Figure 9 it can be read that for asphalt thicknesses 30 cm or greater the influence of uneven load distribution is sufficiently small and may be neglected. For a thickness of 14 cm, however, the influence is considerable; a 60/40 wheel load distribution implies that the maximum shear stress increases 16 percent compared with a 50/50 wheel load distribution. A similar calculation on the same pavement will result in approximately 35 percent increase in stress for a 75/25 wheel load distribution.

Assuming a damage function for rutting based on the exponent 3.3 for the relationship between τ and N, the coefficient for 75/25 wheel load distribution will be in the order of 2.69.

An uneven wheel load distribution of 75/25, a 50 percent increase in the wheel load relative to even load distribution on the dual wheels, will result in a coefficient in the order of 5.0 according to "the fourth power law". Even for asphalt thicknesses of 5 cm it is probably too strict to consider the dual wheels as independent. It is probably more correct to consider the dual tyres individually in a discussion of fatigue cracking than in a discussion of rutting. As a first approximation, a coefficient of 3.0 for both fatigue cracking and rutting is suggested for the 75/25 load distribution.

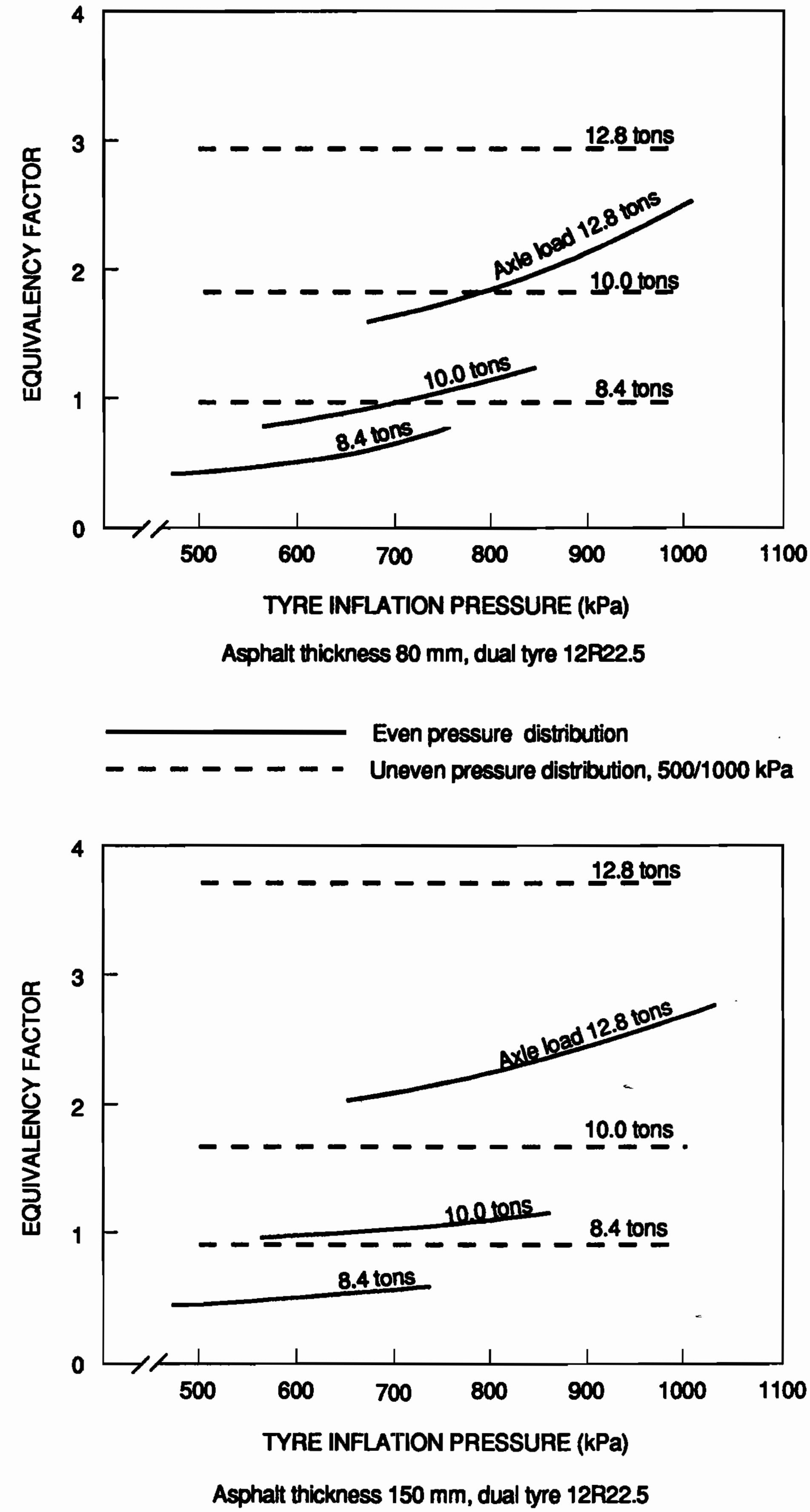
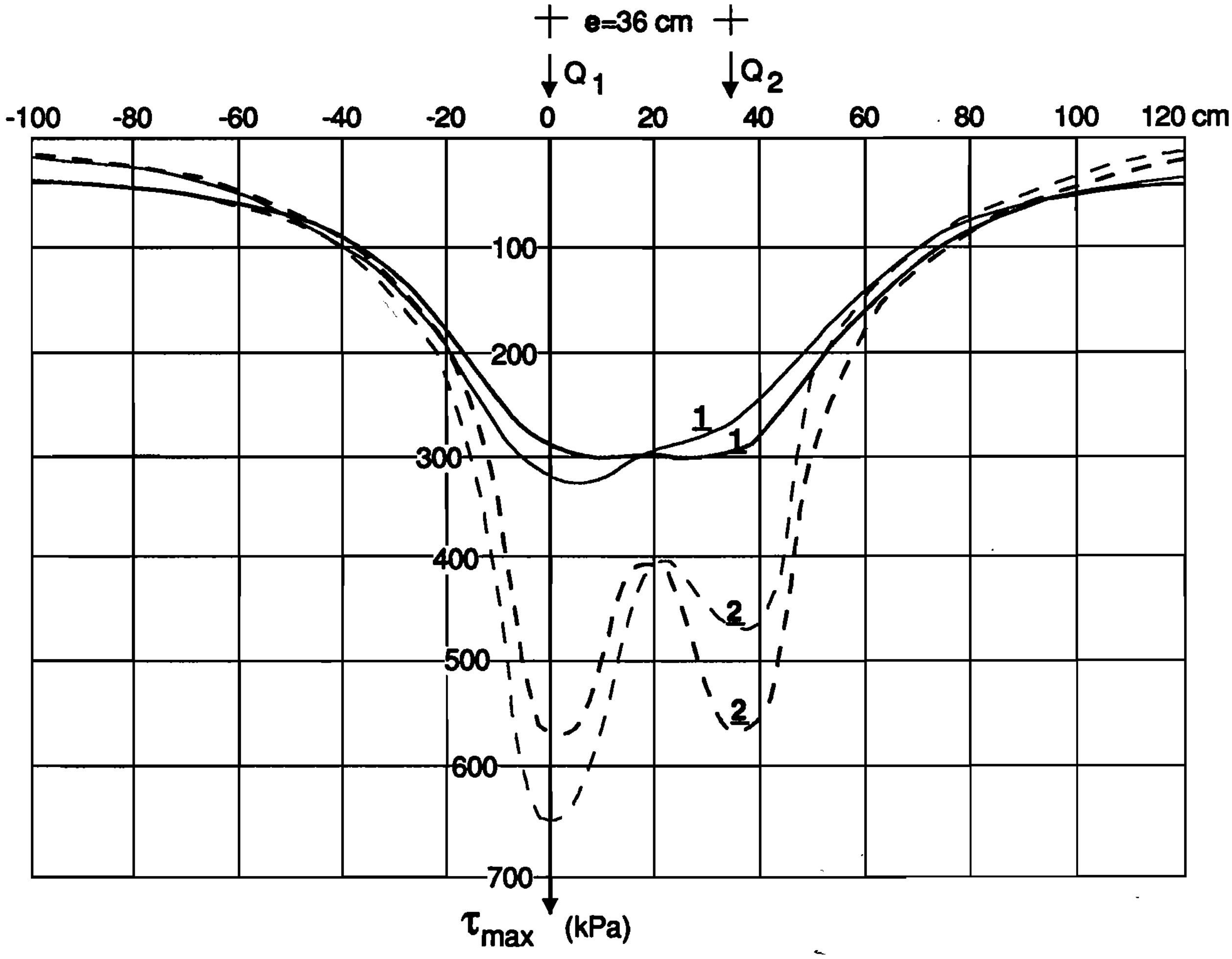


Figure 8: The Virttaa Test Road, the influence of uneven tyre inflation pressure on Load Equivalency Factors, Ref. (2).



LEGEND

1 = asphalt thickness 30 cm
axle load 10 tons
50/50 distribution

2 = asphalt thickness 14 cm
axle load 10 tons
60/40 distribution

e = Center distance (cm) between twin tyres

Thick curves = even wheel load Q1 = Q2 = 2.5 tons
equal contact pressure 610 kPa

Thin curves = uneven wheel load
Q1 = 3.0 tons, contact pressure 710 kPa
Q2 = 2.0 tons, contact pressure 500 kPa

τ_{max} = Maximum shear stress (kPa) below asphalt layer at zero-axis

Figure 9: Primary responses of uneven loaded dual tyres, Ref. (96).

4.4 The axle loads

In most investigations the discussion of the influence of the magnitude of the axle loads on the distress of pavements are focused on the exponent γ in equation (5) or (6), and a multiplication coefficient for the effect of multiple axles.

In the original AASHO-equations the relative damage is based on the reduction in the PSI to a minimum acceptable level, without any dicusssion of which types of distress cause the reduction in the functional performance. Later investigations indicate that the damage criteria have a pronounced influence on the equivalency factors for the actual axle loads.

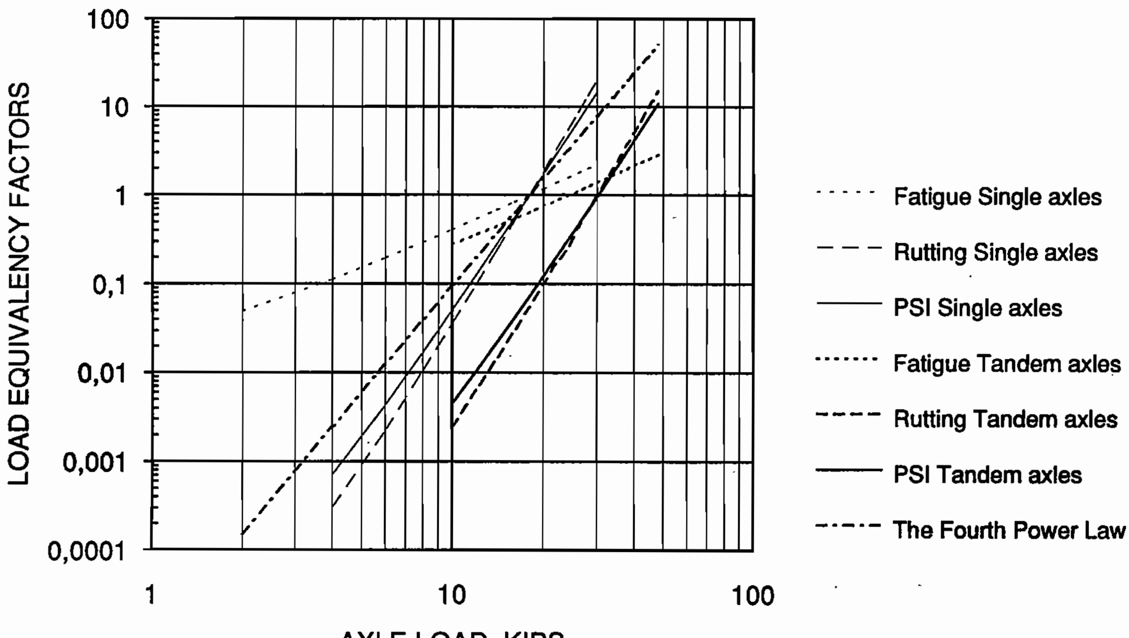


Figure 10: The AASHO Road Test, wet freeze zone, asphalt course thickness 7.5 cm, Subgrade Modulus 1060 MPa (15000 psi). Ref. (65).

Figure 10 is the result of a back-calculation of data from the AASHO Road Test for the wet freeze zone and a pavement structure with 7.5 cm asphalt (65). It is apparent from these data that the magnitude of the axle loads has an influence on the relative amount of fatigue cracking which differs considerably from the influence on rutting and roughness.

The data from Rauhut (65) can be expressed by the use of the exponent γ of equation (6), as shown in Table 15.

Type of axle	Type of distress	Exponent	Load for LEF = 1.0
Single axle	Fatigue cracking	1.48	18 kips
	Rut depth	5.72	18 kips
	Roughness	5.04	18 kips
Tandem axles	Fatigue cracking	1.50	24 kips
	Rut depth	5.60	30 kips
	Roughness	5.02	30 kips

Table 15: Exponents for different types of damages. AASHO.

In the study of Rauhut (65) rut depths and roughness are discussed as two separate criteria. However, the damage prediction models for roughness and rutting are normally not considered independent, both are related to the vertical strain in the subgrade (73) (60). In Table 15 the exponent and the axle load for LEF = 1.0 for rut depth are nearly identical to those for roughness.

4.4.1 Fatigue Cracking

The Nardo test, Italy

At the OECD test in Nardo (10) (60), Italy in 1984 a large variety of axle loads and axle configurations were tested with respect to fatigue cracking. The relative damage was estimated from measured maximum tensile strain in the asphalt, adjusted to a temperature of 25 °C. The estimation of fatigue cracking was based on a damage model used in Italy for bituminous materials.

The exponent γ in equation (6) was found to vary from 1.58 to 2.95 with an average of 2.0. The type of axle and/or tyre configuration did not seem to have an influence on the exponent. The pavement structure in the Nardo test was a 10 cm bituminous layer on a 20 cm unbound granular course.

Another conclusion from the Nardo test was that driving axles was causing more fatigue damage than carrying axles. A 12.5 tons driving tandem was found to be equivalent to a 14.0 tons carrying tandem and a 17 tons carrying triple axle.

The Virttaa test, Finland

In the Virttaa test in Finland in 1987 (2) (41) (42) (60) the influence of the axle loads were investigated on two types of structures, one with 8 cm of asphalt and one with 15 cm asphalt. In this investigation the tyre inflation pressures were not considered independent of the axle load and tyre types. The inflation pressures were adjusted according to the recommendations from the tyre manufacturers.

The horizontal tensile strains at the bottom of the asphalt were measured and the vertical strains in the granular materials were estimated from measured vertical stresses.The relative influence on the pavement damage was estimated by using the damage functions of Shell, based on the tensile strain of the asphalt (fatigue) and the maximum vertical strain in the unbound materials (rutting).

For fatigue the exponent for the influence of the axle loads was found to be as shown in Table 16. After correction for the influence of the various inflation pressures used in these tests to a fixed value, according to the conclusions in Table 7, the exponents are reduced as shown:

Axle type	Exponent before correction	Exponent after correction for infl. pressure
Single axles	3.3	1.8
Tandem axles	4.0	2.5

Table 16: Virttaa Test Road exponents for axle loads, fatigue.

The corrected exponents are higher than the AASHO results for fatigue cracking reported by Rauhut, see Table 14. The differences, however, are not extreme considering the differences in time, applied traffic loads and location of the tests.

The FORCE-project at Nantes, France

The FORCE-project (the First OECD Research Common Experiment) in 1989 (59) (60) was initiated to investigate the effect of an increase in the single axle loads from 10 tons to 11.5 tons. The project also included single axle loads of 8.2 and 13 tons.

The FORCE-project included thin bituminous sections (6 cm asphalt on 30 cm crushed base), thick bituminous sections (13 cm asphalt on 30 cm crushed base) and a bituminous surface on cement treated material (7 cm asphalt on 17 cm cement treated gravel).

The relative influence of single axle loads on fatigue cracking was expressed by the exponent γ in equation (6) as a function of the amount of cracking, measured by both the area of cracking and the total length of crack per length of road. As can be seen in Figure 11, the exponent increases approximately linearily with the observed cracking.

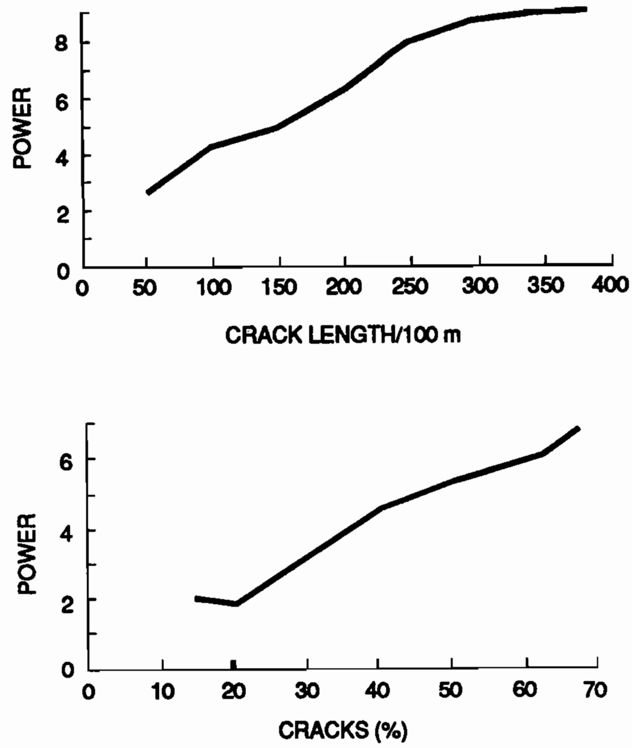


Figure 11: The FORCE-project. The exponent γ expressed as Power, a function of crack length and percentage cracked area, Ref. (59) (60).

If one considers a cracked area of 20 - 30 percent of the total area, as a realistic expression for the maximum acceptable amount of damage, the exponents for fatigue cracking are reported to be in the range of:

Based on percentage of area	γ =	3.2 to 3.7
Based on total length of cracks	γ =	2.7 to 4.3

An exponent γ equal to 3.5 can be considered as an average of the ranges listed above.

Also in the FORCE-project at Nantes the inflation pressure was adjusted according to the recommendations of the tyre producers, see Table 17:

Axle load	Infl. pressure
8.2 tons	600 kPa
10.0 tons	600 kPa
11.5 tons	710 kPa
13.0 tons	850 kPa

Table 17: Axle loads and tyre pressures.
The FORCE project Nantes.

When adjusting for the influence of the inflation pressure, the exponents γ for the axle loads are reduced. A comparison of the effects on fatigue potential of a single axle of 11.5 tons with 710 kPa inflation pressure, to that of 10 tons with 600 kPa inflation pressure results in a reduction in the exponent above from 3.5 to 1.46 in average. The range of variation for the exponent was from 1.00 to 6.81. An exponent of 1.46 is close to those reported by Rauhut (65) and reasonably close to the results for single axles at the Virttaa test (2) (41) (60).

The Canadian Weights and Dimensions Study

During the summer of 1985, pavement surface deflections and asphalt tensile strains at the interface between the asphalt surface and the granular base courses were measured at 14 different locations across Canada (25). For tandem axles the influence of the axle spacing was tested at 1.2 m, 1.5 m and 1.8 m. For triple axles the following axle spacings were investigated: 2.4 m (1.2 + 1.2) , 3.7 m (1.83 + 1.83) and 4.9 m (1.83 + 2.03). In all tests the tyre inflation pressure was kept constant at 690 kPa, and the type of tyre used was 11 R 22.5. The LEF's were calculated from estimated fatigue damages based upon measured asphalt tensile strains.

The equivalency factors expressed by the exponent γ and the axle load for LEF = 1.0 are given in Figure 12. It can be seen that the influence of axle loads is different for single axles than for tandem and triple axles. A regression analysis on the same data provides the results listed in Table 18.

Axle type	Exponent γ	Total load for LEF = 1.0
Single axles	2.0	8.2
Tandem axles	3.3	13.3
Triple axles	3.4	19.0

Table 18: The Canadian Vehicle Weights and Dimensions Study

As for the Virttaa test, the exponent γ is higher for tandem axles than for single axles. In absolute numbers, the exponents from the Canadian study are higher than those from Finland, France and AASHO.

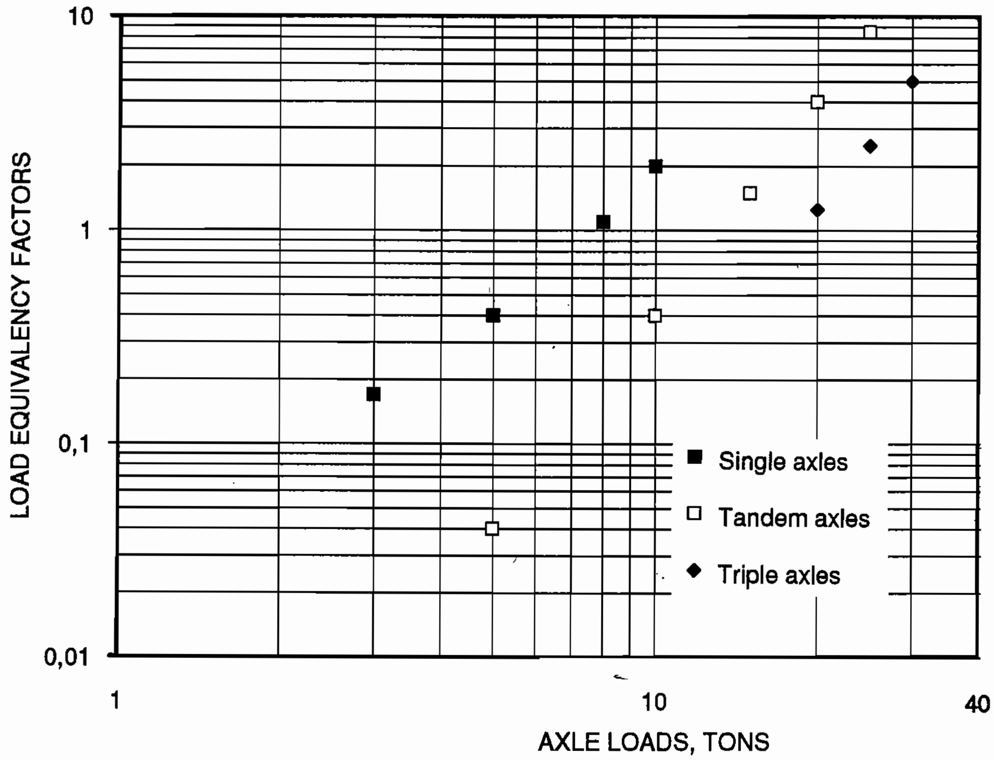


Figure 12: Load Equivalency Factors, The Canadian Vehicle Weights and Dimensions Study, Ref. (25).

From Table 18 it can be concluded that two separate axles of 8.2 tons will cause a relative damage of 2.0 as will a tandem axle of 16.4 tons. Three single axles of 8.2 tons will cause a relative damage of 3.0, while a triple axle of 24.6 tons (3 x 8.2 tons) will correspond to a relative damage of 2.4, i.e. equivalent to the damage of 2.4 passages of a single axles of 8.2 tons.

4.4.2 Permanent deformations

Carpenter (18) has recently investigated the influence of axle loads on the rutting in asphalt, based on data from the AASHO Road Test. Loops 4, 5 and 6 from the AASHO Road Test site were chosen for these analysis due to the cement treated base course underlying the asphalt layers. For these sections the rutting recorded at the surface was considered to be entirely related to permanent deformations within the asphalt itself.

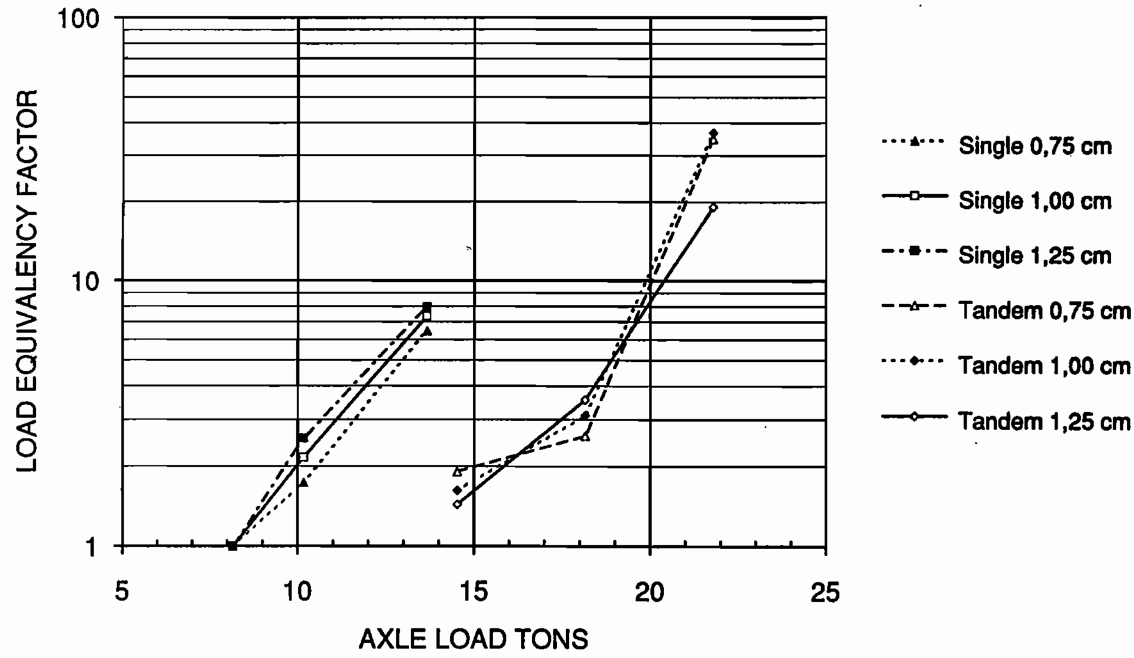


**Figure 13: Rutting in thick bituminous materials
The AASHO Road test, Loop 4, 5 and 6, Ref. (18).**

The findings of the Carpenter analysis (18) are shown in Figure 13 and are expressed as LEF values relative to 8.2 tons single axle load. For single axles a regression analysis of the data in Figure 13 conducted for this report gives values for the exponent γ in the range 3.67 to 4.02 depending on the amount of rut depth chosen as the maximum acceptable. Carpenter proposed 3.89 as the average value. Figure 13 indicates a higher exponent for the tandem axles, in the range of 6.5 to 7.0. The regression analysis, however, are greatly influenced by the extreme values recorded for the 22 tons tandem axles. Rutting recorded for the 22 tons tandem axles, is assumed to be related to damage within the cement treated base courses. The results are for this reason assumed not representative for the rutting in the asphalt. Ignoring these results, Carpenter suggested an exponent of 2.78 and a tandem axle of 12.1 tons having a LEF value of 1.0.

Based on full scale laboratory tests of rutting in asphalt, Peter von Becker (11) suggested an exponent in the order of 2.0 for the relative influence of the single axle loads.

Gillespie et al (34) suggest a linear relationship between the axle loads and the rate of rutting in asphalt. If the axle load is increased by 100 percent, the relative rutting damage will also increase 100 percent. Gillespie therefore related the amount of rutting to the the total vehicle weight rather than to axle loads.

The AASHO Road Test

The original equations from the AASHO Road Test (1) suggest the use of the Present Serviceability Index, PSI, as the damage criterion for acceptable pavement conditions.The amount of rutting and roughness is normally related to the maximum vertical strain in the subgrade as the critical primary response.

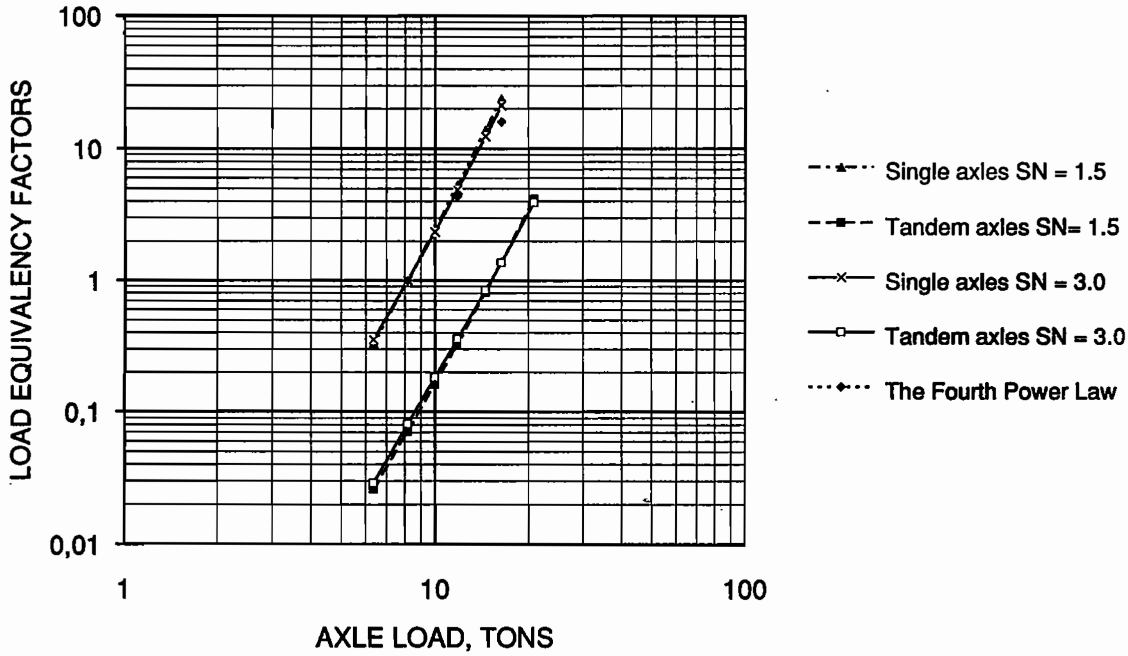


Figure 14: Original AASHO equations, minimum acceptable PSI = 2.0.

The "Fourth Power Law" has been examined by many authors since the AASHO Road Test in 1958 - 1960. The original AASHO equivalency factors correspond to an exponent slightly higher than 4.0 as can be seen from Figure 14.

The STINA Project

Analysis conducted in the STINA project (84) concluded that for traffic situations common in the Nordic countries, the total estimated damage was rather insensitive to the exponent in the range of 3.5 to 5.0.

The FORCE-project, Nantes

In the FORCE-project at Nantes (59), the exponent γ was found to be 5.74 for the 6 cm asphalt section and 2.88 for the 13 cm section. For the thin sections the permanent deformation within the asphalt can be considered small. Thus, the total rut depth is related to deformations in the granular materials.

4.5 Multiple axles

In addition to the AASHO Road Test, the relative damage of multiple axles have been investigated in few tests where the damage is measured. There are a large number of tests reported in the literature where the damage is estimated from measured or estimated primary responses. The conclusions from the tests depend entirely on a correct external calibration of the damage models applied.

Different damage models are discussed by Hajek and Agarwal (36) and can briefly be described as follows:

1: **The Roads and Transport Association of Canada, RTAC.**
The estimated damage of the first axle in a multiple axle configuration is related to the peak of the primary response of that axle. The damage of the consequent passing axles are estimated from the difference between the peak response and the preceeding minumum response. If the response, for instance for tencile strains, crosses the zero value, the compression between the axle passages are neglected.

2: **The University of Waterloo Method.**
The method follows the AASHTO Standard Practice which recommends that the highest peak and the lowest valley is calculated first, followed by the second largest cycle, etc. untill all peak counts are included.

3: **The Peak Method.**
The peak method uses the total response under each axle from the rest position for the surface deflection and the subgrade strain. For the interfacial strains, the peak strain is defined as the differences between maximum and minimum recorded strains.

4: **The Strain Energy**
The strain energy method is an intergration method based upon the work done internally by the body. This work is equal to and opposite in direction to the work done upon the body by the external forces.

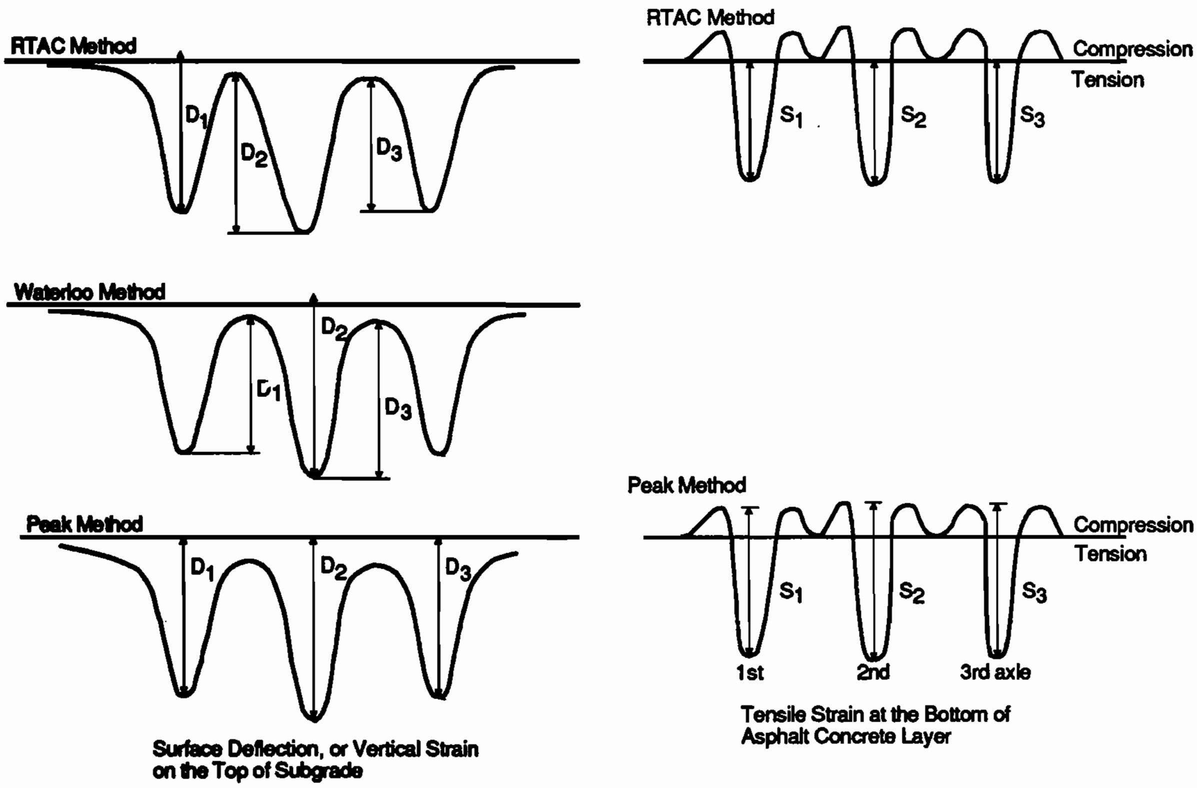


Figure 15: Damage models for multiple axles, Ref. (36).

The first three methods are discussed by Hajek and Agarwal (36) and are shown in Figure 15. Southgate and Deen (82) have discussed the influence of a large number of different factors based on a strain energy model calibrated to the AASHO Road Test.

In addition to the models above Hudson et al. (40) have discussed different methods to calculate the equivalency factors for triple axles from the tandem axles. Five different options were discussed:

1: Use the tandem axle equivalence factors for triple axle loads. This option was considered too conservative.

2: Determine the tandem axle load factor for 2/3 of the triple axle load and add 50 percent to account for the third axle.

3: Determine the single and tandem axle load equivalency factors for 1/3 and 2/3 of the triple axle load respectively, then add the two together.

4: Determine the ratio of the tandem axle to the single axle load equivalency factor and assume the ratio is the same as the ratio of the triple axle to the tandem axle.

5: Determine the ratio of the actual tandem axle equivalency factor to the sum of two single axles having half the tandem axle loads. Then, multiply this ratio by the expected triple axle load equivalency factor obtained from 1.5 times the tandem axle having two thirds the load.

Based on a discussion of the results of the five options calculated for five different loads, option 5 was selected as the best model for estimating triple axle load equivalency factors for roads constructed in Arizona, USA.

4.5.1 Tandem axles

Tables 16 and 18 list different exponents for single axles and tandem/triple axles with respect to fatigue cracking, while Table 14 reports exponents independent of the axle configuration in question. A higher exponent for tandem and triple axles will indicate that the load spreading effect is reduced as the axle load increases. Assuming an exponential relationship between the axle load and the Load Equivalency Factor (a linear relationship in the log - log scale), the tandem and triple axle groups approach the behaviour of a singel axle with an axle load equal to the total load of the group. This is clearly indicated in Figure 12 from the Canadian Heavy Vehicle Weights and Dimensions Study (25). Figure 12 also indicates, however, that an exponential regression for single axles has an acceptable accuracy within the investigated range of axle loads, but care must be taken if the relationship is extrapolated to higher axle loads.

For thin asphalt layers the tandem axle group can be considered very similar to individual single axles, with the absence of rest periods as the main difference. The coefficient for the load equivalency factor will for tandem axles be close to 2.0 for all realistic values of axle spacing, as indicated in Figure 16. This conclusion is in agreement with Figure 17 (34) showing that for a 7.5 cm asphalt thickness, the flexible pavement fatigue was increased by only 4 percent with respect to the effect of axle spacing even for the most extreme cases investigated.

For pavements with weak base courses there are reasons to believe that the discussions above are valid also. This means that tandem axles can be considered as indvidual axles for axle spacing in the range of 1.0 - 1.8 m.

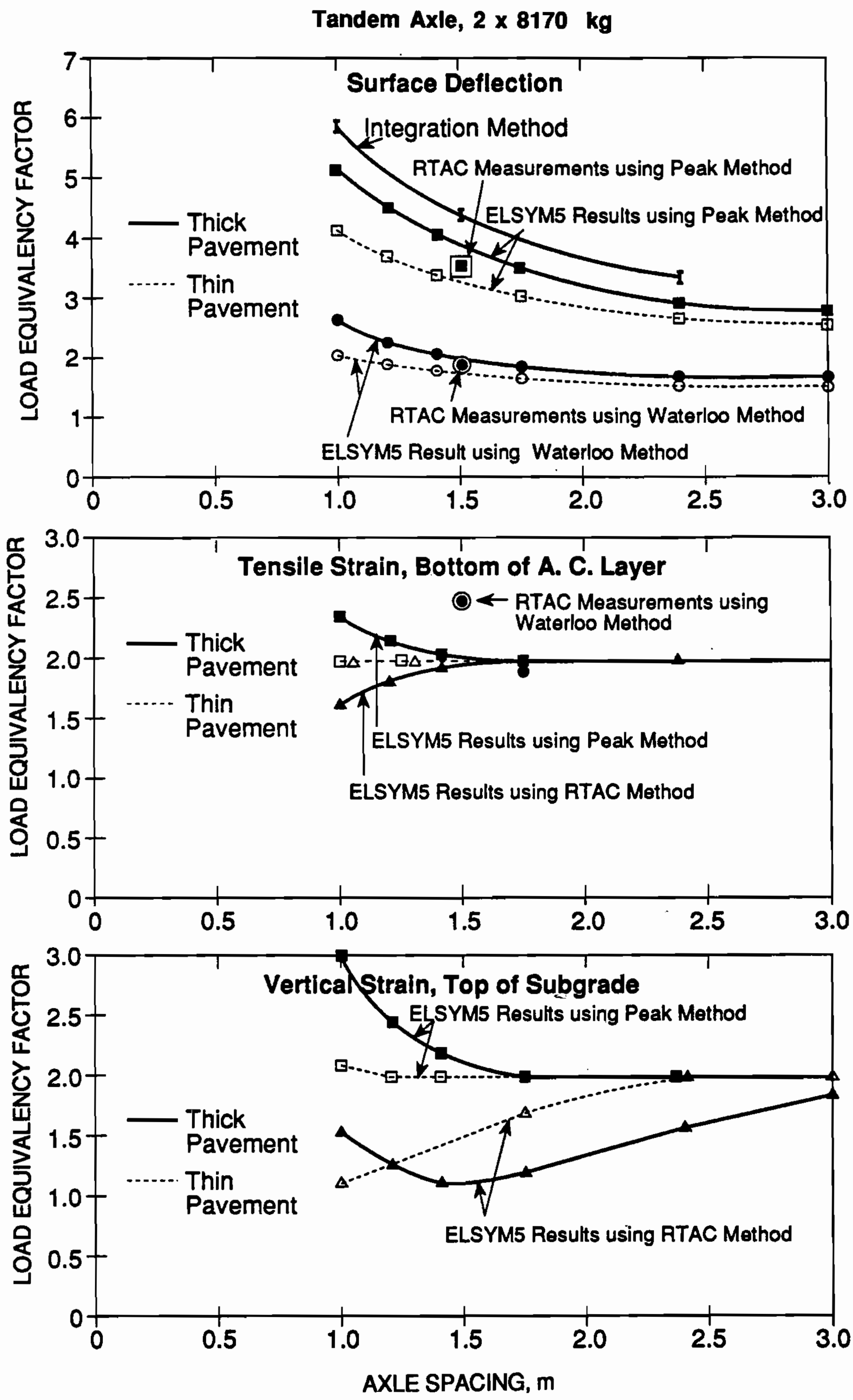


Figure 16: Influence of axle spacing on the Load Equivalency Factor for tandem axles, Ref. (36).

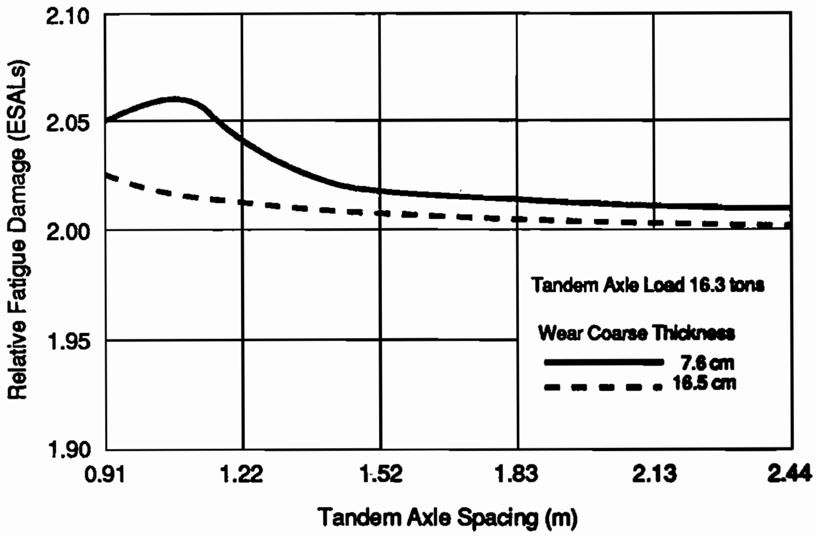


Figure 17: Influence of tandem axle spacing on flexible pavement fatigue, Ref. (34).

For pavements with base courses of "normal" strength, the AASHO equivalency factor for tandem axles corresponds to a coefficient of 1,38. This is in agreement with the conclusions of the RTAC Method presented in Figure 16.

Southgate and Deen (72) express the influence of the axle spacing by the expression :

$$Log(Adj.) = -1.589746 + 1.505262 \times Log(Sp) - 0.3373569 \times (Log(Sp))^2 \quad (11)$$

where Adj. = the adjustment factor for axle spacing of tandem axles.
Sp = the axle spacing of tandem axles, inches

Equation (11) is valid for axle spacings greater than 1.37 m. For 1.80 m the coefficient is increased by 7.7 percent relative to 1.40 m. Figure 16 indicates factors in the range from 1.75 to 1.2, which correspond to an increase of 23 percent. The conclusions of Hajek and Agarwal (36) are in agreement with the AASHO equations and measured damage. Field observations are generally considered more reliable than results from analytical analysis. The suggested coefficients for tandem axles and tandem axle spacing are given in Table 19:

Axle spacing, m	1.00	1.20	1.40	1.60	1.80
Fatigue cracking	2.00	2.00	2.00	2.00	2.00
Roughness and rutting, weak base course	2.00	2.00	2.00	2.00	2.00
Roughness and rutting, strong base course	1.05	1.25	1.40	1.55	1.75

Table 19: Coefficients for tandem axle spacing.

Uneven load on tandem axles

For the influence on fatigue cracking and rutting/roughness for weak base course materials, the conclusion by considering the axles within a tandem axle configuration as individual single axle loads, will also be valid for uneven loading of the tandem axles.

Assuming an exponent of 1.5 for fatigue cracking (see Table 15), the coefficient for 25/75 axle load distribution will be 1.10. For the same conditions, an exponent of 4.0 for rutting of weak base course materials will result in a coefficient equal 2.6.

For rutting of subgrade under a strong base course, the situation is more complex. The axles can no longer be considered individually as the primary responses at a depth of 60 - 70 cm are influenced by the total load within the axle configuration as well as the individual wheel loads.

Southgate and Deen (82) express the influence of uneven load of tandem on the pavement damage by the equation:

$$Log(MF) = 0.0018635439 + 0.0242188935 \times \% - 0.0000907 \times (\%)^2 \qquad (12)$$

where: MF = a Multiplication Factor expressing the influence of uneven load on tandem axles

$$\% = \frac{(Axle\ load\ 1 - Axle\ load\ 2) \times 100}{Axle\ load\ 1 + Axle\ load\ 2} \qquad (13)$$

Equation (12) results in a multiplication factor equal to 9.7 for a 25/75 axle load distribution, which intuitively is far too great. By adopting the principles of Hudson et al. (40) and Option 5 in estimating the equivalency factor of triple axles from tandem, the coefficient for 25/75 distribution of load on tandem axles will be the same as for the case with a weak base course.

4.5.2 Triple axles

The triple axles are partly discussed already, and much of the principles for tandem axles are also valid for triple axles.

For the fatigue of thin asphalt surface courses the coefficient for triple axles will be 3.0. This implies that the three axles cause the same damage as three individual single axles, with the possible inaccuracy for the absence the influence of rest periods as with tandem axles.

The coefficient 3.0 will also be the equivalency factor for rutting and roughness from triple axles on weak base course materials.

The AASHTO Guide for Design of Pavement Structures (3) provides equivalency factors for triple axles as well as for single and tandem axles. For a triple axle of 24.5 tons (3 x 8.2 tons) the equivalency factor is 1.66 independent of the Structural Number of the pavement structure and the minimum acceptable Serviceability Index. This value is only 55 percent of the sum of equivalency factors for three individual axles of 8.2 tons. The coefficient corresponds to the coefficients for the RTAC Metod in Figure 18. From this the coefficients for triple axles have been estimated as shown in Table 20.

Axle spacing, m	**1.20**	**1.40**	**1.60**	**1.80**
Fatigue cracking	3.00	3.00	3.00	3.00
Roughness and rutting weak base course	3.00	3.00	3.00	3.00
Roughness and rutting, strong base course	1.50	1.90	2.20	2.50

Table 20: Coefficients for triple axle spacing.

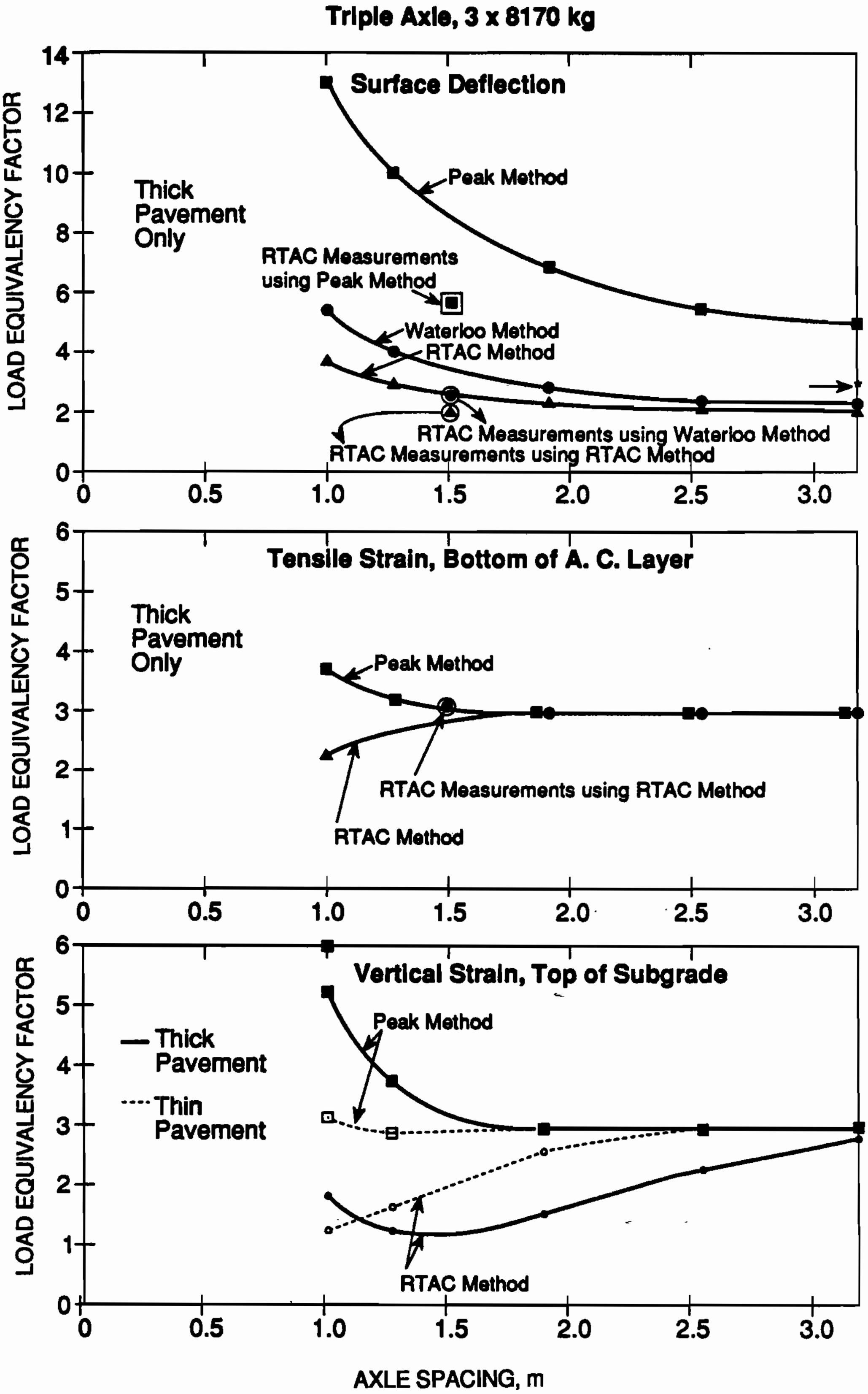


Figure 18: Influence of axle spacing on the Load Equivalency Factors for triple axles, Ref. (36).

Uneven load on triple axles

There exists a wide range of alternatives for uneven load distributions on triple axles, depending on the degree of uneveness between the individual axles. Southgate and Deen (82) have calculated the damage factors for 5 different loading conditions. The factors are related to a variable noted as "Ratio", defined as the ratio between the difference of the heaviest and the lightest axle loads and the intermediate axle load. Regression equations set forth by Southgate and Deen (82) result in very high factors, up to more than 50 for a "Ratio" equal 1.00.

As for the uneven load distribution of the tandem axles, the coefficients for triple axles calculated from the regression equations refered to above, are much higher than is intutively accepted. A reasonable estimate may for uneven loads on triple axles be based on the same principle as for uneven loads on tandem axles: to calculate the axles individually and mulitply the average LEF per axle with the coefficients shown in Table 20.

For a triple axle with 50/25/25 load distribution the coefficients will be 1.05 for fatigue cracking and 1.9 for rutting and roughness of asphaltic pavements on unbound materials. Both coefficients are considerably smaller than those from the regression equations of Southgate and Deen (82).

5 Interactions between the factors

In the discussions above the influence of most of the different factors are generally regarded as independent of the other influences, with little or no interactions. Figures 19 and 20, taken from Reference (34), show the interactions between the various factors in Strong, Weak and No interactions for fatigue and rutting interactions respectively. In addition to the factors included in this survey, Figures 19 and 20 include factors as speed, tandem dynamics, etc.

A comparison of Figure 19 with Figure 20 indicates a larger number of interactions for asphalt fatigue than for rutting.

	Vehicle/Tyre Factors	Axle loads	Gross weight	Axle spacing	Static load sharing	Speed	Single axle susp. type	Tandem dynamics	Maneuvering	Inflation pressure	Single, dual, wide-base	Ply type	**Pavement Factors**	Roughness	Surface temperature	Wear coarse thickness	Base layer thickness	Subgrade strength
Vehicle/Tyre Factors																		
Axle loads		●																
Gross weight			●															
Axle spacing				●														
Static load sharing				○	●													
Speed						●												
Single axle susp. type						○	●											
Tandem dynamics						●		●										
Maneuvering		○	○			○	○	○	●									
Inflation pressure		●						○		●								
Single, dual, wide-base		●		○	○		○	○		●	●							
Ply type		○								●	○	●						
Pavement Factors																		
Roughness						●	○	●						●				
Surface temperature				●	●					○	●	○			●			
Wear coarse thickness			○	●	●					●	●	○			●	●		
Base layer thickness					○						○				○	●	●	
Subgrade strength					○					○	○					○		●

● = Strong interaction ○ = Weak interaction (blank) = No interaction

Figure 19: Flexible pavement fatigue interactions, Ref. (34).

For rutting a strong interaction is indicated between the tyre type, tyre configuration and the tyre inflation pressure. An interaction is also indicated between pavement roughness, vehicle speed and suspension characteristics. There is, however, only indicated a weak interaction between the axle load and the tyre inflation pressure.

For asphalt fatigue the strong interactions are the same as for rutting. In addition, an interaction is indicated for axle load, tyre type and configuration. This is in agreement with the conclusions in Table 6. There is also indicated an interaction between axle loads, surface layer temperature and thickness.

	Vehicle/Tyre Factors	Axle loads	Gross weight	Axle spacing	Static load sharing	Speed	Single axle susp. type	Tandem dynamics	Maneuvering	Inflation pressure	Single, dual, wide-base	Ply type	**Pavement Factors**	Roughness	Surface temperature	Wear coarse thickness	Base layer thickness	Subgrade strength
Vehicle/Tyre Factors																		
Axle loads		●																
Gross weight			●															
Axle spacing				●														
Static load sharing					●													
Speed						●												
Single axle susp. type							●											
Tandem dynamics						○		●										
Maneuvering			○			○	○	○	●									
Inflation pressure		○								●								
Single, dual, wide-base		○						○		●	●							
Ply type										○	○	●						
Pavement Factors																		
Roughness						●	○	●						●				
Surface temperature										○	●	○			●			
Wear coarse thickness			○							○	●	○			●	●		
Base layer thickness											○					○	●	
Subgrade strength																		●

● = Strong interaction ○ = Weak interaction (blank) = No interaction

Figure 20: Flexible pavement rutting interaction, Ref. (34).

6 Conclusions

The discussion of the relative influence of traffic related factors on the performance and functional damage of flexible road pavements has been related to equation (6):

$$LEF = k_{at} \times k_{wt} \times k_{ld} \times k_{tp} \times \left(\frac{P}{P_0}\right)^{\gamma} \quad (6)$$

where
- k_{at} expresses the effect of axle type, including the axle spacing
- k_{wt} expresses the effect of wheel type.
- k_{ld} expresses the effect of uneven load distribution on dual tyres
- k_{tp} expresses the effect of tyre pressure
- P the load on one axle
- P_0 the reference load on one axle
- γ the exponent for the influence of the axle load

For the influence of the axle load, it is necessary to use two different values for the exponent γ depending on whether fatigue cracking or rutting is expected to be the dominating pavement distress. For fatigue cracking several investigations indicate an exponent close to 1.5. For rutting and roughness the literature study indicates a larger range of variation for the exponent . A value of 4.0 will, however, represent a reasonable average.

The exponents 1.5 and 4.0 will result in the influence of the single axle load on flexible pavement damage as shown in Table 21.

Single axle load, tons	4	6	8	10	12	14
Fatigue cracking	0.25	0.46	0.72	1.00	1.31	1.66
Rutting and roughness	0.03	0.13	0.41	1.00	2.07	3.84

Table 21: The influence of single axle loads.

For the influence of axle configuration and single axle spacing on a tandem or triple axle configuration, it is considered necessary to apply different coefficients for rutting and roughness depending on the strength of the base course.

Axle spacing, m	1.00	1.20	1.40	1.60	1.80
Fatigue cracking	2.00	2.00	2.00	2.00	2.00
Roughness and rutting, weak base course	2.00	2.00	2.00	2.00	2.00
Roughness and rutting, normal base course	1.05	1.25	1.40	1.55	1.75

Table 22: Coefficients for tandem axle spacings.

Axle spacing, m	1.20	1.40	1.60	1.80
Fatigue cracking	3.00	3.00	3.00	3.00
Roughness and rutting weak base course	3.00	3.00	3.00	3.00
Roughness and rutting, normal base course	1.50	1.90	2.20	2.50

Table 23: Coefficients for triple axle spacings.

For a tandem and triple axle configuration with uneven load distribution the Load Equivalency Factor (LEF) can be calculated from Tables 21 and 22 or from Tables 21 and 23 respectively as described in the following example:

Example: A tandem axle of 18 tons is assumed to have a load distribution on the axles of 1/3 and 2/3 respectively. For an axle spacing of 1.40 m and a strong base course the Load Equivalency Factor with respect to **roughness** will be:

The loads on the axles will be 6.0 tons and 12 tons. The average LEF per axle is then (0.13 + 2.07)/2 = 1.10 according to Table 21. From Table 22 the coefficient for tandem axles is 1.40 which gives:

LEF for the axle configuration: 1.10 * 1.40 = 1.54

For the influence of the tyre inflation pressure on **asphalt fatigue cracking** it is recommended to use the coefficients in Table 24 from Southgate and Deen (82):

Tyre inflation pressure	600 kPa	800 kPa	1000 kPa
Single tyre, bias tread	0.78	1.00	1.26
Single tyre, radial tread	0.59	1.00	1.56
Dual tyre, bias tread	0.87	1.00	1.15
Dual tyre, radial tread	0.72	1.00	1.35

Table 24: Tyre pressure coefficients, fatigue.

For **roughness and rutting** it is suggested to apply the coefficients in Table 25:

Tyre inflation pressure	600 kPa	800 kPa	1000 kPa
Bias tread tyre	0.77	1.00	1.32
Radial tread tyre	0.67	1.00	1.39

Table 25: Tyre pressure coefficients, rutting.

For single tyres it is suggested to apply the coefficients in Table 26:

Single tyre width, inches	10	12	14	16	18
LEF coefficient	3.99	2.91	2.19	1.68	1.25

Table 26: Single tyre coefficients, roughness and rutting.

The coefficients in Table 26 may be used for fatigue of asphalt layers of thickness 10 - 15 cm and greater. The coefficients cannot be applied for fatigue cracking of very thin asphalt layers, 5 cm and smaller.

As a consequence of the interaction between axle load and tyre inflation pressure, the coefficients in Tables 24 and 26 are restricted to single axle loads of 8 tons and greater. For other axle configurations the corresponding lower load limits will be in the order of 15 and 22 tons for tandem and triple axles respectively.

For lighter axle loads the influence of tyre type and tyre inflation pressure are higher than indicated in Tables 24, 25 and 26, as indicated in Table 6. However, in most calculations the overall error by using Tables 24, 25 and 26 for lighter axle loads is relatively small because of the small coefficients for the lighter axles as shown in Table 21.

For an uneven distribution of loads on dual tyres the LEF coefficients in Table 27 are suggested:

Load distribution. on tyres	**50 / 50**	**75 / 25**
LEF coefficient	1.0	3.0

Table 27: LEF coefficient for uneven distribution on dual tyres.

It is important to keep in mind that all the coefficients in the tables above are related to equation (6). As one example, Table 24 shows that the LEF for dual tyres radial tread is less sensitive to the tyre inflation pressure than the LEF of single tyres radial tread. Table 24 does, of course, not indicate that single tyres are less damaging than dual tyres at a tyre inflation pressure of 600 kPa.

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Appendix 1

Axle load restrictions on public roads in Norway

In Norway, as in most other countries, there are detailed restrictions on the weights and dimensions of the heavy vehicles on public roads. Some of the most important regulations are given in Table 28 below.

Maximum allowable load on a single carrying axle is 10 tons, while the limit for the drive axle is 11.5 tons. When the distances between the individual axles in tandem or triple axles are less than 1.20 m, the maximum allowable load on tandem and triple axles are less than shown in Table 28.

Max allowable axle loads, single axle	10 tons
Tandem axle, axle distance 1.30 - 1.80 m	18 tons
Tandem axle, axle distance 1.20 - 1.29 m	16 tons
Triple axles, axle distance 1.30 - 1.80 m	24 tons
Triple axles, axle distance 1.20 - 1.29 m	22 tons
Max. allowable gross weight	50 tons

Table 28: Allowable axle loads, Norway.

In addition to these general regulations, axle load restrictions are applied on the allowable axle loads during spring thaw periods for a major part of the public roads. (80)

Table 29 provides a general overview of the current practice of axle load restrictions in general and during the spring thaw periods for the National and the County Road network.

Road category	10 tons	8 tons
National Roads, no restrictions in the spring thaw	22%	5%
National Roads, additional restrictions in the spring thaw.	56%	17%
County Roads, no restrictions in the spring thaw.	4 %	18 %
County Roads additional restrictions in the spring thaw.	25 %	53 %

Table 29: Percentage of road lengths with axle load restrictions for National and County Roads.

The total length of National roads is 26.300 km, and the County road network consists of 27.000 km.

Restrictions in the maximum allowable axle loads are applied during the periods of the year when the road structure temporarily undergoes a reduction in bearing capacity. In principle, the period of reduction, as well as the load reduction itself, are set individually for each route each year, depending on the climatic situation and the estimated reduction of the bearing capacity of the road.

For some roads the axle load limits during the winter periods with frozen ground are increased to 10 tons. The allowable total vehicle gross weight, however, are not increased during these periods.

Reduced allowable axle loads, in general or for a limited time of the year, are regarded by the industry in Norway as a major handicap. There has for many years been a great pressure on the Public Roads Administration to provide a public road network with 10 tons allowable axle loads, and to mimimize the use of load restrictions during the spring thaw periods.

Appendix 2

Pavement response and distress

The analysis of traffic loads and pavement damages may be based on direct measurements of traffic and damage, as was the case in the AASHO Road Test in 1958 - 60 (1). Full scale trials of this kind are, however, extremely expensive and time consuming. Full scale field tests will normally also be influenced by the temperature and other climatic effects in an uncontrolled manner.

Investigations of all the different factors which may be of any significance to pavement distress and functional damage will have to be based on combinations of different methods of measurements and analytical analysis. The different analysis may be classified in three groups as follows:

1: **Controlled traffic loads and measured damage**

The AASHO Road Test in Illinois (1) and the OECD Force Project at Nantes (59) may be considered representative for this type of analysis. Although it is not really necessary for the conclusions, the tests will normally include some type of pavement response measurements. The response measurements will serve as helpful means in the control of the conclusions, as well as a calibration tool for other damage models.

After more than 30 years the data from the AASHO Road Test are still commonly used for verification or calibration of new distress models.

This group will also include analysis based on estimated pavement response and measured damage. Estimated response will not have the instrumentation limitation and inaccuracy of measured response models. On the other hand, these models may suffer from other inaccuracies, for instance due to the simplification of the material properties or inaccuracies in the description of the responses.

The use of Accelerated Loading Facility, ALF, such as the facilities at the FHWA in the U.S.A and the ARRB in Australia (46), will naturally be in this group of analyses.

2: **Controlled traffic loads and estimated road damage**

A typical example of this group of analyses will be the Virttaa test road in Finland (2) (56) (41), where the traffic factors are carefully controlled and the pavement responses are measured. The calculation of the influence on pavement damage depends on the validity and the accuracy of damage models for transforming the response measurements into an estimated damage.

This group of analysis will include measurements of pavement response of roads subjected to normal traffic at different test sites. The Canadian Heavy Vehicle Weight and Dimensions Study is representative for these tests (24) (25). For these type of tests there will normally be some practical limitations to the amount and type of response measurements. In its most simplified version only deflections are measured.

3: **Estimated traffic loads and estimated damage**
In this group we will find the analytical models combining estimated response calculations to damage models. Using analytical calculations most factors influencing the pavement response and damage may be investigated independently or as a factor interacting with others.

The reliability of the conlusions from the analytical calculations will depend entirely on the models for estimating the primary responses, the models for the material properties in the pavement, as well as the models for estimating the damage.

It will always be necessary to calibrate the analytical models to the damage which occur to roads in service. When material properties from laboratory tests are used, it will be necessary to take into account the in situ variability of the properties in the pavement. There will also be a need for a calibration of the models for the effects from factors not included in the models.

Functional performance

Damage functions, often also called damage prediction models, may be defined as expressions of normal functional performance prediction equations (37). In the literature, however, the damaging force of the traffic related factors are based on different criteria (73) (48):

* Serviceability, functional performance
* Structural damage
* Primary response
* Cost of repair of the pavement

Changes in roughness and rut depths are primarily measures of functional distress, while fatigue cracking is primarily considered as structural wear. It is generally accepted that only extreme cracking has a significant influence on the functional performance.

From a structural point of view, however, fatigue cracking of a flexible pavement is important, both for its influence on the reduction in the load spreading capacity and for the reduced water protection of the underlying unstabilized materials. Excessive water within the various materials may cause a reduction of the bearing capacity and provide conditions for excess wear of the structure.

The use of primary responses alone as independent damage criterias, is highly questionable. In most cases, the primary responses are used for linking the loads to damage by general or specially developed damage models.

The cost of repair is of vital significance for the road authorities and this criterion is occationally used in special studies. There will always be a level of structural and/or functional performance dictating resurfacing and reconstruction. However, criteria based on the costs of repair, ignoring and not taking into account the impact of the pavement functional performance on the road users costs, are generally not accepted.

Cracking

The criteria used in estimating the relative influence of different variables on the damage of road pavements, will depend on how the damage is measured as well as other factors. In the FORCE-project in Nantes (59), the damaging effect of fatigue cracking is expressed as a function of the amount of cracking. A minimum acceptable standard of 20 - 30 percent cracked area, or 60 - 100 m cracks per 100 m road, may be used as a reasonable criterion.

The criterion presented by Finn et al. (33) is adopted by many investigators: maximum 10 percent cracked area of the wheel path. Unfortunately, the definition of cracked area differs significantly in the various criteria.

Rut depth

Measurement of rut depths is in principle a relatively simple task. There is now available on the market high speed equipments which make it possible to measure rut depths of the entire road network.

There may be some differences in the use uf rut depth criteria whether the focus is on visco-plastic deformations in thick bituminous layers (16) or permanent deformations in the unbound base course or subgrade material. Several ivestigators (34) (96) assume the relationship between the asphalt rutting and the traffic loads to be primarily linear. The discussion of asphalt rutting is therefore independent of a damage criterion.

Longitudinal roughness

Roughness is closely related to the riding comfort and therefore considered to be the most important damage criterion. The AASHO Road Test (1) expressed the longitudinal roughness by the Slope Variance, from measurements using the AASHO or the CHLOE Profilometer.

There are a large number of different equipments for measuring the longitudinal roughness of a road surface, based on different principles. The damage criteria for roughness have to be related to the method and the equipment in use. Unfortunately, the Slope Variance of the AASHO Road Test is based on a rather unstable and unpractical measuring method, and is now entirely replaced by other methods. The International Roughness Index, IRI, has been adobted by many road authorities (61) (72).

The Present Serviceability Index, PSI

In Norway the different damage criteria discussed above, are considered independent. The need for resurfacing due to rut depths are discussed independent of the longitudinal roughness, and vice - versa.

In many investigations the different criteria are combined in a overall serviceability criteria, such as a minimum acceptable level of the Present Serviceability Index, PSI.

The AASHO Road Test used the Present Serviceability Index, PSI, as a measure of the functional performance of a road pavement. The PSI was related to the properties of the road surface by the expression:

$$PSI = 5.03 - 1.91 \times Lg(1.0 + SV) - 0.01 \times \sqrt{c+p} - 1.38 \times RD^2 \qquad (14)$$

where:
- SV = Slope variance, an expression of the longitudinal roughness of the pavement
- c = Cracked area, square feet per 1000 square feet
- p = Patched area, square feet per 1000 square feet
- RD = Rut depth, inches

The PSI expresses the functional condition or the performance of a pavement and is related to a subjective rating by the road users. A reduction in PSI is generally accepted as a measure of the functional damage of the pavement.

The PSI will normally be in the order of 4.2 for a new or newly resurfaced pavement. The lowest acceptable service level for a pavement will generally correspond to a PSI of 2.0. For major trunk roads a minimum acceptable PSI level of 2.5 is used by several road authorities.

The PSI is dominated by the roughness of the pavement. Rut depths of 10 mm (0,4 inches) will only cause a reduction in the PSI of 0.2, and a 100 percent cracked or patched surface will reduce the PSI in the order of 0.1. Assuming that the functional performance is closely connected to the riding comfort, the dominance of the roughness on the PSI is not very surprising.

The original AASHO equations (1) related the pavement damage to the equivalent numbers of 8.2 tons (18 kips) single axle dual tyre load repetitions by regression equations for the changes in the PSI from a new road in perfect condition to the minimum acceptaple level of serviceability. It is inherently assumed that the changes in the PSI expresses the structural damage of the pavement.

Damage prediction models

The damage prediction models serve as a tool for relating measured or estimated primary responses to damage predictions. The most widely used damage models are:

* A relationship of the maximum asphalt tensile strain (as the primary response) to the asphalt fatigue cracking.

* A relationship of the maximum vertical subgrade strain (as the primary response) to the rut depth.

In earlier studies the surface deflections were commonly used as the primary response in damage models for both fatigue cracking and serviceability loss.

The damage models may be expressed by regression equations for full scale damage tests or expressed by mechanistic models, usually based on laboratory tests. Damage prediction by mechanistic models will need some type of internal and external calibration.

The internal calibration will primarily serve to adjust the material properties in the models to the actual field conditions. The external calibration will normally serve to adjust the damage models based on simplified or idealized laboratory tests to a more complex situation in the field. The use of shift factors are typical for the external calibration of damage models.

Fatigue cracking

Most investigations relate the fatigue cracking to the maximum initial strain of the bituminous material, by the adoption of a model based on the relationship:

$$\varepsilon_i = A \times N^B \tag{15}$$

where ε_i = the initial tensile strain of the asphalt
N = the number of load application to failure

The coefficients A and B above vary considerably among the investigators, as is indicated below:

Research Projects	A	B
Virttaa (Shell fatigue)	17.8×10^{-4}	-0.165
Nardo, Italy	47.4×10^{-4}	-0.234
FORCE, Nantes (10°C)	19.5×10^{-4}	-0.20
UK Rolled asphalt	5.9×10^{-4}	-0.20

Table 30: Fatigue models obtained from major research projects.

Finn et al. (31) propose a similar model for 10 percent cracking in the rut area, combining the initial tensile strain and the E-modulus of the asphalt:

$$Log N_{10} = 15.947 - 3.291 \times \left(\frac{\varepsilon_i}{10^6}\right) - 0.854 \times Log\left(\frac{E}{10^3}\right) \tag{16}$$

where N_{10} = the number of load repetitions to 10 percent cracking in the wheel paths
ε_i = the initial tensile strain in the asphalt
E = the E-modulus of the asphalt, (psi)

The equation above is derived from combining the results form the AASHO Road Test with laboratory test results. (A similar equation is derived for 45 percent cracking).

Permanent deformation , rutting

Some investigators discuss the development of ruts in bituminous layers as a integrated part of the whole structure and base their discussion on the maximum subgrade vertical strain as the expression for the primary response, while others consider the deformation in bituminous materials to be related to completely other mechanisms based on a different damage model.

The FORCE project relates the discussion of the permanent deformation of the whole structure on the damage model:

$$D = a + b \times N^k \tag{17}$$

where D = the average rut depth
N = the number of load application
a and b = regression coefficients

and where the exponent k often is assumed to be 0.5.

The coefficient b is used as a basis for discussions of the sensitivity of the asphalt materials to rutting, as well as the relative influence of other factors. Eisenmann and Hilmer (31) and Peter von Becker (11) discuss the permanent deformation of asphalt materials based on the same equation.

Majidzahdeh (51) relates the deformation and the permanent strain to the primary responsen by the equation:

$$\varepsilon_p = 3.6 \times \left(\frac{\sigma_c}{E^*}\right)^{1.08} \times N^m \tag{18}$$

where the exponent m is in the range of 0.13 to 0.27.

The MOEBIUS damage model (59) is based on a "dynamic creep test" and expresses the permanent deformation in the bituminous materials and the subsequent rutting by two separate regression equations

$$\varepsilon_a = \alpha \times t^\beta \tag{19}$$

$$\varepsilon_a = A \times t \tag{20}$$

where t expresses the time under load , α, β and A are functions of the temperature, the horizontal and vertical stress.

Several damage prediction models are based on the equation 21 where ε_z is the vertical strain on the subgrade and N the number of load repetition to failure:

$$\varepsilon_z = A \times N^B \tag{21}$$

Longitudinal roughness

Equation 21 is used both for estimating the rutting as well as the longitudinal roughness. Both the World Bank's Highway Design and Maintenance Standard Model (HDM) (59) and VESYS (33) consider the roughness model as a function of the variations of the rut depths. Assuming the surface of the pavement in areas not subjected to traffic loads remain prefectly even, the roughness in the wheel paths is the consequence of variations of permanent deformations due to the traffic loads.

On many roads, however, the traffic loads are not the only cause for longitudinal roughness. In Norway frost heave, frequent and large variations in the subgrade material properties are essential to the roughness of the road surface. A damage model based on the correlation between the rut depth variance and the roughness will probably have to be rejected.

Appendix 3

The serviceability of pavements in Norway

In the literature it is generally assumed that there is reasonably close relationship between traffic loads and the functional distress of the flexible pavements. This relationship needs to be discussed in the light of very different mechanisms of functional distress observed on Norwegian roads:

* For roads with traffic volumes larger than approximately 3000 in AADT, the development of ruts in the wheel paths is mainly wear of the surface due to the use of studded tyres during the winter. The development of ruts caused by permanent deformations in the pavement or in the subgrade is relatively small compared to the wear from studded tyres. Potential distresses due to heavy traffic loads are often hidden by frequent resurfacing of the pavement caused by studded tyre wear. Traditional resurfacing will also increase the bearing capacity of the pavements independent of the structural situation.

  For roads with AADT less than 3000 the wear from studded tyres is no longer a dominant factor for rehabilitation and maintenance. The road inventory for 1991 (91) shows that 83 percent of the National Road network and 97 percent of the County Road network have AADT < 3000.

* Effects of traffic loads are probably not as dominant in Norway as in other countries for the development of roughness. Factors as frequent changes in the subgrade materials, variability in the compaction of unbound materials during the road construction, uneven frost heave and variability in the recompaction of materials after frost heaves, all have another distress mechanisms than those which are discussed in connection with traffic loads.

  This situation is illustrated in Figure 21 from Edsvalla Test Road in Sweden (84) where the surface characteristics are expressed by a TRAC index, in principle comparable with the AASHO Present Serviceability Index. For six of the test sections an increase in the TRAC-index with time is observed. This is in direct conflict with most damage models which inherently assume a reduction in the PSI with time.

* A major part of the Norwegian road network, in particular roads with AADT less than 3.000, has evolved in time from paths for horse carts to paved roads in a rather obscure manner. Only a

small part of the network is constructed in regular manners according to specifications and standards.

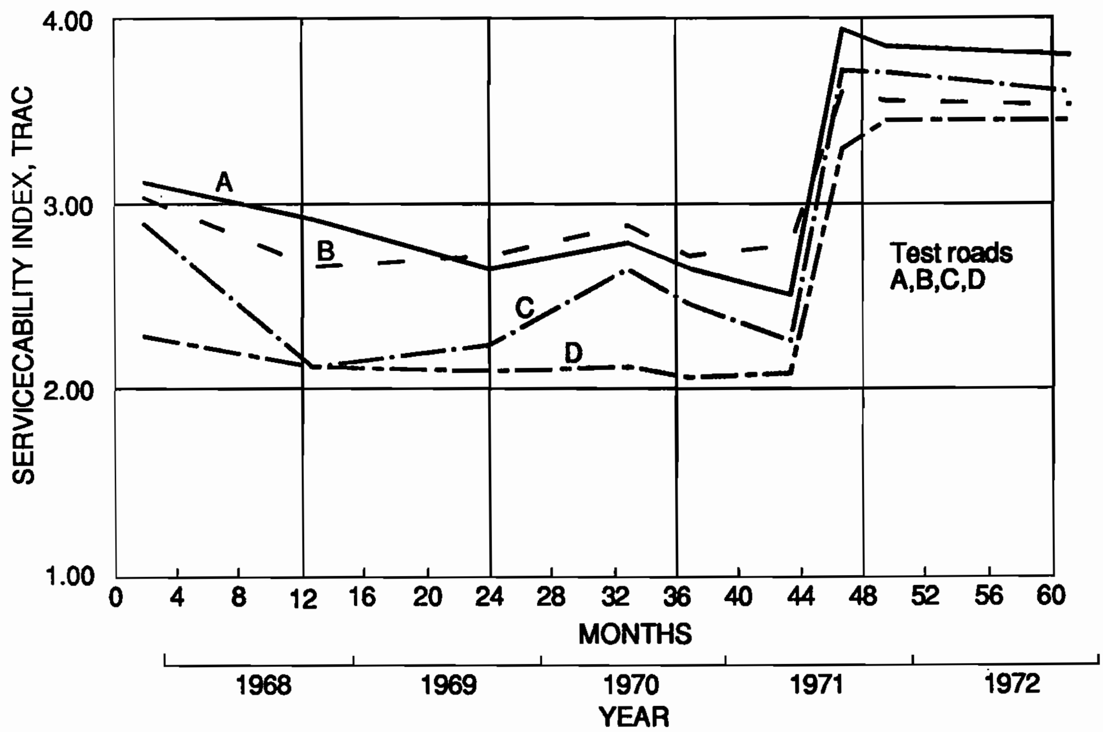


Figure 21: Serviceability index for Test Roads A, B, C and D in the Scandinavian STINA-project, Sweden, Ref. (84).

Adoption of damage models from the international literature to roads in Norway require an examination of the damage criteria in the light of the maintenance standards set forth by the Norwegian Public Roads Administration, NRRL.

In the Norwegian Public Road and Road Traffic Plan for 1994 - 97 the proposed maintenance criteria for resurfacing of the roads are expressed by maximum allowable rut depths and longitudinal roughness IRI. The criteria are for the 90/10 distribution for road sections, normally of 3 - 5 km lengths (90 percent of the section shall have rut depths and IRI values smaller than the criteria). According to the Norwegian experience, the 90/10 distributions are 50 - 60 percent higher than the average values. The proposed maintenance criteria are shown in full in Appendix 4.

The criteria for both rut depths and longitudinal roughness are given independently. No efforts have been made so far to express these surface characteristics in one maintenance criterion, such as the PSI. In a previous proposal the amount of cracking was included in the criterias for road surface maintenance. However, little efforts have so far been made to develop a system for registration of cracking on a network level. Cracking is not taken into account in the present proposed criteria.

In order to compare the PSI-based criteria in the literature with the Norwegian criteria for road surface maintenance, a survey of the pavement surface characteristics of the public roads in 4 of the total 19 counties within Norway have been conducted. The counties were selected in order to ensure geographical and climatic variations. It was also required that a minimum of 85 - 90 percent of the National Roads within the counties were surveyed for roughness and rut depths in 1991. The required percentage of roads with measurements was appled in order to ensure objective data collection.

The National Road network is for maintenance purposes divided into PM-sections (Pavement Management sections) of various lengths, each section considered to be relatively homogeneous with respect to the maintenance needs. The PM-sections for the 4 selected counties consist of some 5000 km of roads which is approximately 20 percent of the total length of this network, see Table 31.

County	No. of PMS-sections	Road length Km.
Buskerud	536	1082
Aust-Agder	249	878
Sør-Trøndelag	325	1406
Troms	519	1664
TOTAL	1629	5029

Table 31: Investigated PM-sections.

For each PM-section the average roughness and the rut depth are presented in Figure 22 and separated in three groups with respect to the AADT:

$$AADT < 300$$
$$300 \leq AADT < 1000$$
$$1000 \leq AADT < 3000$$

PM-sections with AADT greater than 3000 are not included because of the influence from the studded tyre wear on the registered rut depths.

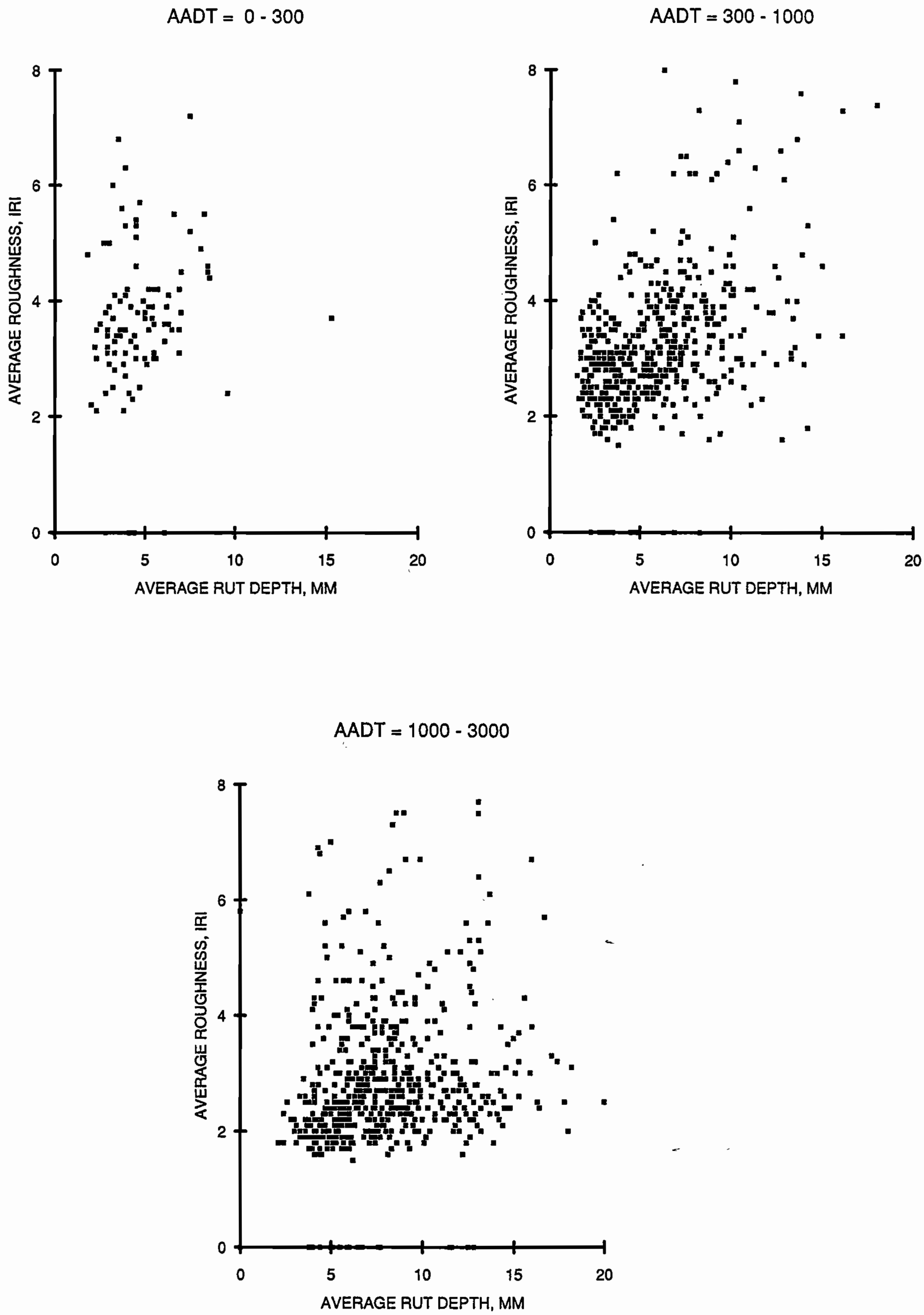


Figure 22: The relationship between rut depth and roughness IRI for National Roads in 4 counties in Norway.

Taking into account for a 50 - 60 percent increase for the relationship between the 90/10 and the average values for both roughness and rut depths, Figure 22 indicates clearly that roughness is the dominant triggering factor for pavement resurfacing according to the maintenance criteria set forth in the Norwegian Road and Road Traffic Plan 1994 - 97 (see Table 32 and 33 in Appendix 4).

In order to compare the data based on roughness IRI with the AASHO equation for PSI, it is necessary to transfer the Slope Variance to IRI values. Roughness data based on two different measuring principles are not easily compared without a risk of high inaccuracies. The comparison is made in three ways:

* Roughness measurements in Finland 1983 (8) are combined with the International Road Roughness Experiment in Brazil in 1982 (72).

* Roughness measurements in Sweden in 1975 (84) are combined with measurements in Denmark 1989 (49).

* The relationship recommended by Paterson (61) which is based on a large number of comparison studies.

The test in Finland makes the use of a TRAC-value , and the STINA-project uses NIT-values, both are supposed to express PSI of paved roads in Scandinavia.

Ignoring the element for cracked and patched area, the equation for the relationship between roughness, rut depth and the PSI will be:

$$PSI_{TRAC} = 6.22 - 1.31 IRI^{1.12} - 0.00214 RD^2 \qquad (22)$$

according to the combination of the tests in Finland and Brazil, and:

$$PSI_{NIT} = 4.52 - 0.83 \times IRI - 0.00214 \times RD^2 \qquad (23)$$

for the combination of the STINA-project with the recent study in Denmark.

Paterson recommended the following equation for comparing IRI with PSI:

$$IRI = 5.5 \times Ln\left(\frac{5.0}{PSI}\right) \qquad (24)$$

The relationship for a large number of studies between IRI and PSI are shown in Figure 23 (61). The Paterson relationship (often refered to as the World Bank relationship) seems to correlate better with what is intuitively expected for the roads in Norway, in spite that the STINA/Danish correlation include the equipment used in Norway for measuring longitudinal roughness. The STINA/Danish equation corresponds to what is noted as the NCHRP228 relationship in Figure 23.

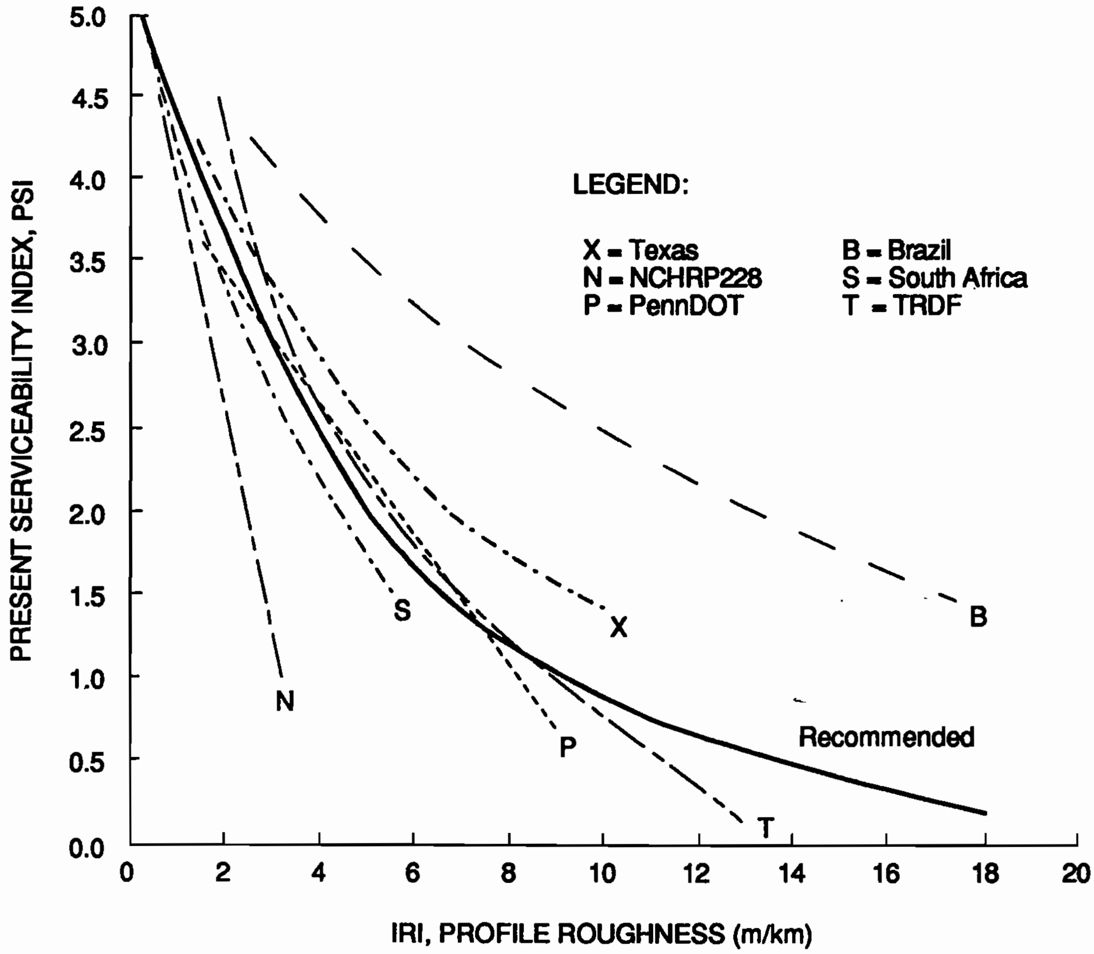


Figure 23: Present Serviceability Index, PSI, versus Profile Roughness IRI from five international studies, Ref. (61).

Knowing that the choise of correlation have a sigificant influence on the comparison and evaluation of the structural and functional "health" of road pavements in Norway, the main conclusions will be:

* The maintenance criterias for rut depths express almost entirely the pavement wear from studded tyres. For roads with AADT less than 3000 very few roads seem to need resurfacing or other maintenance efforts due to ruts.

* If PSI-values of 2.0 or even 1.5 was applied as a maintenance criterion, a major part of the National Roads seem to be in a critical need for resurfacing or even reconstruction if the STINA/ Danish correlation is to be applied. The situation is more "normal" if one apply the World Bank correlation.

* There are reasons to believe that the development of longitudinal roughness is the result of many factors. Traffic loads and structural damage attribute only to a small portion of the total roughness.

* For this study damage equations and equivalency values for the different traffic factors based on roughness or the PSI, will in general have a priority to fatigue cracking and ruts caused by permanent deformations. However, due to lack of knowledge concerning the relationship between the amount of rutting caused by the traffic loads (excluding the wear from studded tyres) and rutting by other mechanisms, fatigue and permanent deformation criteria should not be ignored.

A programme for annual inventory of rut depths and longitudinal roughness of the National and County Roads in Norway has been active for the last 2 - 4 years. Compiled data for several years for the same road sections will provide a better background for drawing conclusions with respect to the causes of functional distress of the roads in Norway.

Appendix 4

Maintenance criteria for flexible pavements - public roads in Norway

The Norwegian Public Road and Road Traffic Programme for 1994 - 97 includes a proposal for maintenance criteria for flexible road pavements based on measured rut depths and roughness.

For the transverse rut depths the proposed criteria are shown in Table 32.

AADT	< 1000	1000 - 5000	> 5000
Trunk Roads	25 mm	20 mm	15 mm
Other National Roads Speed limit 70 - 90 km/h	25 mm	25 mm	20 mm
Other National Roads Speed limit ≤ 60 km/h	35 mm	30 mm	25 mm

Table 32: Maintenance criteria, rut depths.

For the longitudinal roughness expressed in IRI, the criteria are shown in Table 33.

AADT	< 1000	1000 - 5000	> 5000
Trunk Roads	IRI = 4.5	IRI = 4.0	IRI = 3.5
Other National Roads Speed limit 70 - 90 km/h	IRI = 5.0	IRI = 4.5	IRI = 4.0
Other National Roads Speed limit ≤ 60 km/h	IRI = 6.5	IRI = 6.0	IRI = 5.5

Table 33: Maintenance criteria, longitudinal roughness.

For both rut depth and roughness the initiation of maintenance is related to the 90/10 distribution. This implies that for maximum 90 percent of the total road length the measured rut depth and longitudinal roughness shall not exceed the criteria in Tables 32 and 33 above.

It is, however, important to notice that the criteria are related to the road network. Minimum 90 percent of the National Roads in each County shall comply with the criteria. The criteria are not applicable on the road maintenance section level.

It must also be noticed that the criteria are related to the pavement surface conditions at the end of the paving season. For a road with AADT greater than 5000, a speed limit of 60 km/h and an estimated service life of the surface layer in the order of three years, the maximum rut depth of 25 mm in the Autumn will be acceptable.The rut depth for this road may then be as high as 37 mm by the end of the following Winter season.

Fatigue cracking

The maintenance criteria do not include maximum values for cracking and patching.

In a previous proposal, "Vedlikeholdsstandard for Statens vegvesen" of December 1985, the surface maintenance criteria included maximum levels of cracked area:

Roads with AADT > 1500 : 10 percent
Roads with AADT < 1500 : 15 percent

In the present discussions of road maintenance there are no intentions of including fatigue cracking in the maintenance criteria.

Appendix 5

Calculation Examples of Load Equivalency Factors

The following calculation examples may serve as illustrations of the use of the coefficients in Chapter 6 of this report.

VEHICLE 1

Front axle: Single wheels, width 12 inches, 6 tons axle load
Drive axle: Tandem axle, dual wheels, 12 tons axle load
Trailer axle: Tandem axle, dual wheels, 16 tons axle load

The tyre inflation pressure: 800 kPa for all tyres

Axle spacing on tandem: 1.60 m

Even distribution of the loads on the dual wheels and on the axles in the tandem configuration.

Rutting	Front axle	Drive axle	Trailer axle	Sum
Tyre type	2.91	1.00	1.00	
Axle load	0.13	0.13	0.41	
Axle spacing	N.A.	1.55	1.55	
LEF	0.38	0.20	0.64	1.22

Conclusion: On a pavement structure of normal strength, Vehicle 1 has a Load Equivalency Factor of 1.22 relative to a 10 tons single axle, dual wheels with respect to rutting.

Fatigue	Front axle	Drive axle	Trailer axle	Sum
Tyre type	1.00	1.00	1.00	
Axle load	0.46	0.46	0.72	
Axle spacing	N.A.	2.00	2.00	
LEF	0.46	0.92	1.44	2.82

Conclusion: Vehicle 1 has a Load Equivalency Factor of 2.82 relative to a 10 tons single axle, dual wheels with respect to fatigue cracking.

For each axle the LEF is obtained by a multiplication of the coefficients for each factor. The vehicle LEF equals the sum of the LEF of the axles.

On a pavement structure of weak base the coefficient of axle spacing equals 2.00 for the drive and the trailer axles with respect to rutting. The LEF of Vehicle 1 will then be 1.46. With respect to fatigue cracking the LEF of Vehicle 1 will be unchanged, 2.82.

VEHICLE 2

Front axle: Single wheels, width 12 inches, 6 tons axle load
Drive axle: Tandem axle, dual wheels, 12 tons axle load
Trailer axle. Tandem axle, dual wheels on one axle, single wheels on one axle, width of single wheel 16 inches, 16 tons axle load

The tyre inflation pressure: 800 kPa for all tyres

Axle spacing on tandem: 1.60 m

Even distribution of the axle loads on the dual wheels and on the axles in the tandem configuration.

Rutting	Front axle	Drive axle	Trailer axle 1		Sum
Tyre type	2.91	1.00	1.00	1.68	
Axle load	0.13	0.13	0.41	0.41	
Axle spacing	N.A.	1.55	1.55		
LEF	0.38	0.20	0.85		1.43

Conclusion: On a pavement structure of normal strength, Vehicle 2 has a Load Equivalency Factor of 1.43 relative to a 10 tons single axle, dual wheels with respect to rutting.

Fatigue	Front axle	Drive axle	Trailer axle	Sum
Tyre type	1.00	1.00	1.00	
Axle load	0.46	0.46	0.72	
Axle spacing	N.A.	2.00	2.00	
LEF	0.46	0.92	1.44	2.82

Conclusion: Vehicle 2 has a Load Equivalency Factor of 2,82 relative to a 10 tons single axle, dual wheels with respect to fatigue cracking.

VEHICLE 3

Front axle: Single wheels, width 12 inches, 8 tons axle load
Drive axle: Tandem axle, dual wheels, 16 tons axle load
Trailer axle: Triple axle, single wheels, width 16 inches, 24 tons axle load

The tyre inflation pressures: 800 kPa for the tyres on the front and the drive axles, 1000 kPa for the tyres on the trailer axles

Axle spacing on tandem and triple axles: 1.60 m

Even distribution of the loads on the dual wheels and on the axles in the tandem and triple axle configurations.

Rutting	Front axle	Drive axle	Trailer axle	Sum
Tyre type	2.91	1.00	1.68	
Axle load	0.41	0.41	0.41	
Axle spacing	N.A.	1.55	2.20	
Tyre infl. pressure	1.00	1.00	1.39	
LEF	1.19	0.64	2.11	3.94

Conclusion: On a pavement structure of normal strength, Vehicle 3 has a Load Equivalency Factor of 3.94 relative to a 10 tons single axle, dual wheels with respect to rutting.

Fatigue	Front axle	Drive axle	Trailer axle	Sum
Tyre type	1.00	1.00	1.00	
Axle load	0.72	0.72	0.72	
Axle spacing	N.A.	2.00	2.00	
Tyre infl. pressure	1.00	1.00	1.56	
LEF	0.72	1.44	2.25	4.41

Conclusion: Vehicle 3 has a Load Equivalency Factor of 4.41 relative to a 10 tons single axle, dual wheels with respect to fatigue cracking.

VEHICLE 4

Front axle: Single wheels, width 12 inches, 8 tons load
Drive axle: Tandem axle, dual wheels, 18 tons load, uneven distributed on the individual axles, 8 and 10 tons .
Trailer axle. Triple axle, single wheels, width of wheel 16 inches, 24 tons axle load, uneven dirstibuted on the individual axles: 6 tons, 12 tons and 6 tons.

The tyre inflation pressures: 800 kPa for the tyres on the front and the drive axles, 1000 kPa for the tyres on the trailer axles

Axle spacing on tandem and triple axles: 1.60 m

Even distribution of the loads on the dual wheels.

Rutting	Front axle	Drive axle		Trailer axle			Sum
Tyre type	2.91	1.00		1.68			
Axle load	0.41	0.41	1.00	0.13	2.07	0.13	
Axle spacing	N.A.	1.55		2.20			
Tyre infl. pressure	1.00	1.00		1.39			
LEF	1.19	1.09		3.99			6.27

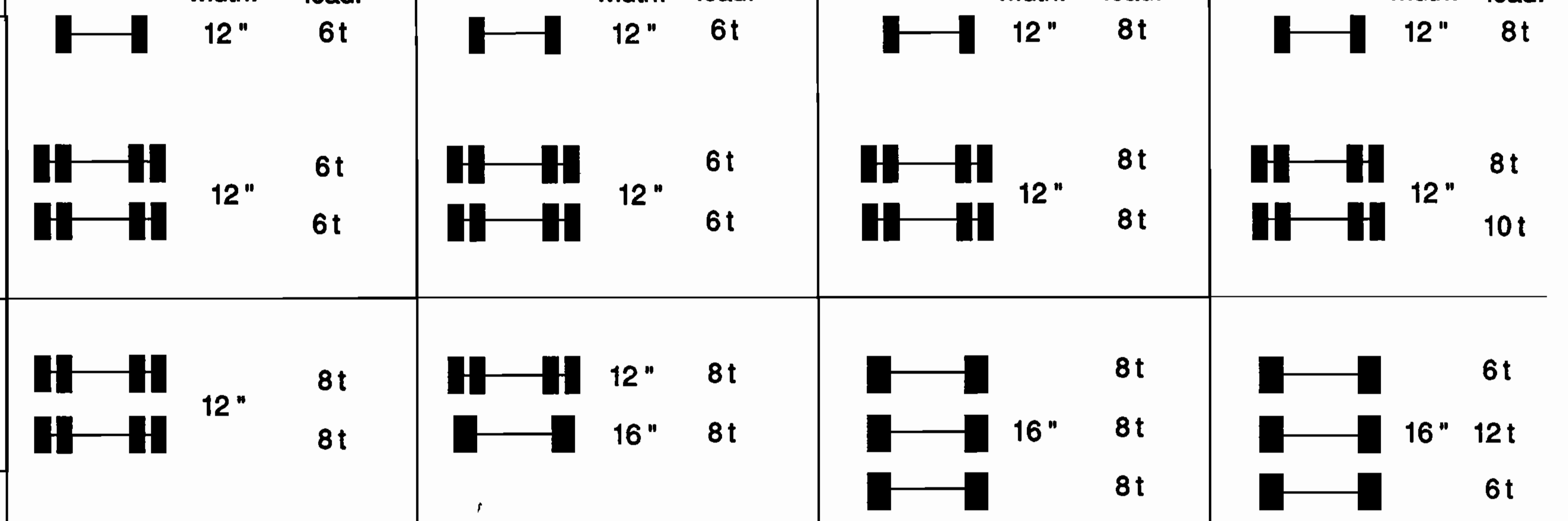
Conclusion: On a pavement structure of normal strength, Vehicle 4 has a Load Equivalency Factor of 6.27 relative to a 10 tons single axle, dual wheels with respect to rutting.

Fatigue	Front axle	Drive axle		Trailer axle			Sum
Tyre type	1.00	1.00		1.00			
Axle load	0.72	0.72	1.00	0.46	1.31	0.46	
Axle spacing	N.A.	2.00		3.00			
Tyre infl. pressure	1.00	1.00		1.56			
LEF	0.72	1.72		3.48			5.92

Conclusion: Vehicle 4 has a Load Equivalency Factor of 5.92 relative to a 10 tons single axle, dual wheels with respect to rutting.

Appendix 5 - Calculated LEF

Examples:



		Vehicle 1		Vehicle 2		Vehicle 3		Vehicle 4	
		Tyre width:	Axle load:	Tyre width:	Axle load:	Tyre width:	Axle load:	Tyre width:	Axle load:
Truck unit	Single axle	12 "	6 t	12 "	6 t	12 "	8 t	12 "	8 t
	Tandem axle	12 "	6 t / 6 t	12 "	6 t / 6 t	12 "	8 t / 8 t	12 "	8 t / 10 t
Trailer		12 "	8 t / 8 t	12 " / 16 "	8 t / 8 t	16 "	8 t / 8 t / 8 t	16 "	6 t / 12 t / 6 t
Load Equivalency Factors (LEF):	Rutting:	1.22		1.43		3.94		6.27	
	Fatigue:	2.82		2.82		4.41		5.92	

NOTE:
- -Axle spacings in tandem and triple configurations are 1.60 m,
- -Dual tyres are equally loaded.
- -Tyre inflation pressure equals 800 kPa.
- -Equal load transfer left and right hand side of vehicle.

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