Vehicle wheel loads and road pavement wear

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SYNOPSIS

Current knowledge of the influence of vehicle parameters on pavement wear is described, including axle configuration and the type of wheel assembly used. Further confirmation of the overall relationship between axle weight and pavement wear is presented, and the conditions under which departures from this relationship occur are noted. The effects of vehicle suspension on dynamic loading of a pavement are discussed, and the need for development of models of pavement response and performance able to take these into account is noted.

1. INTRODUCTION

Traffic-induced wear of road pavements depends mainly on the wheel loading imposed by commercial vehicles. Although the static axle loads of heavy goods vehicles using the road has traditionally been considered the main determinant of pavement deterioration, the influence of other vehicle parameters is also significant. These include:

- type of axle (number of wheels and type of tyres)
- axle arrangement
- surface contact pressure of tyre
- suspension system

Singly, or in combination, these variables affect the basic structural wear mechanism acting in the pavement, and thereby influence the static axle load - wear relationship. Quantification of these effects has been the subject of research in various countries over recent years; this paper summarises what is known at present about the effects of some vehicle parameters, with particular reference to the UK, and indicates those areas where uncertainties remain.

2. THE FOURTH POWER LAW

The fourth power law was derived from large-scale experiments carried out by the American Association of State Highway Officials (AASHO) between 1958 and 1961 (Highway Research Board 1962). In this factorial experiment, a series of road pavements was constructed in the form of loops, each having sections of widely differing strengths. Different types of heavy vehicles, with single axle weights varying between 0.9 tonnes and 13.6 tonnes, and tandem axles between 10.9 tonnes and 21.8 tonnes, were driven over the roads in a continuous stream, each road carrying vehicles of one axle configuration only. The deterioration of all the sections of the roads was monitored throughout the two year duration of the experiment. From the results of the experiment, the Road Test Equation was derived which related a given amount of physical deterioration of the pavement to the number of applications of a given axle load.

One of the implications of the Road Test Equation is the fourth power law, relating the damaging effects of two axle loads. The law has been frequently subjected to careful scrutiny, because of its implications for pavement design, maintenance policies, and, in the United Kingdom, heavy goods vehicle taxation policies. Generally the law has been found to be robust, although theoretical work, by Addis and Whitmarsh (1979) for example, suggests the possibility of departures from the law when exceptionally heavy axle loads are applied to weak pavements, and vice versa. Nonetheless, they concluded that for most design and maintenance purposes, the fourth power law best described the static axle load - road wear relationship.

More recently, experimental work carried out under the auspices of OECD (Organisation for Economic Cooperation and Development) has tended to substantiate the theoretical conclusions of Addis and Whitmarsh.

The experiment, known as FORCE, and reported fully elsewhere (OECD 1991), had a number of different scientific objectives. Among these was a study of the relative damage effects of two different axle loads, of 10 Tonnes and 11.5 Tonnes, chosen because of their particular relevance to European legislation. This was investigated by the simultaneous application of the two loads to adjacent tracks of three road pavements of widely differing strengths. The results of the experiment, during which approximately 4 million load applications were made to each pavement, were analysed on the separate bases of the observed rutting and cracking of the pavements.

Heavy vehicles and roads: technology, safety and policy. Thomas Telford, London, 1992.

2.1 THE FORCE EXPERIMENT

The experiment was carried out by 15 countries and organisations acting in collaboration under the auspices of OECD. The test facility operated by Laboratoire Central des Ponts et Chaussées (LCPC) at Nantes, France, and described fully by Autret and Gramsammer (1987), was offered as a possible site for the test. For the purposes of the FORCE test, the facility met the principal criteria required, namely:

a) A capability of testing three different structures simultaneously.

b) A capability of simultaneously applying a different load on each of two different tracks.

c) Good stability of wheel loading, and minimum effects due to changes in the level of the pavement surface as a result of the provision of strengthening layers.

d) A high rate of application of wheel loads (2400 per hour) and unsupervised operation of the facility.

Figure 1 shows a schematic view of the test facility; it incorporates four 20 m-long arms that are driven round the track by 1000 HP hydraulic motors. A twin wheel assembly attached to the extremity of each arm allows an equivalent axle load of between 8 and 13 tonnes to be applied to the pavement at speeds of up to 100 km/h. Loads may be applied to the pavement through either single or tandem axle assemblies, and wheel assemblies can be moved to and fro across the track to reproduce the effects of traffic.

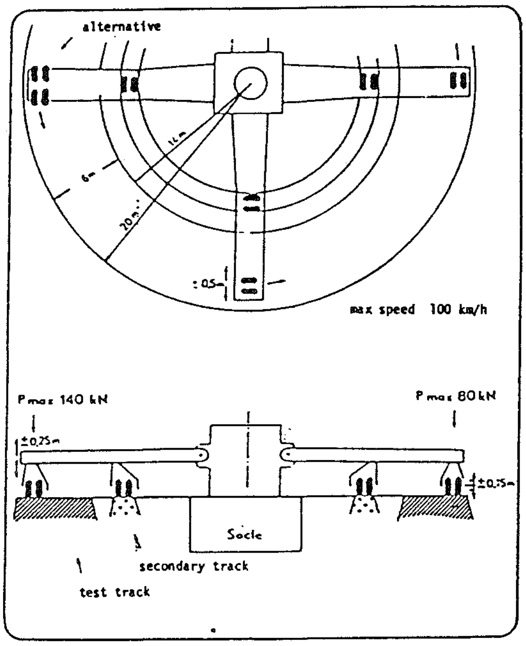

Fig. 1. Schematic view of test facility

Details of test structures

The test was carried out on three pavements, typical of designs used for different traffic categories in a number of the participating member countries.

Structure 1: A thin construction, comprising:
60 mm bituminous layer on
300 mm of crushed aggregate

Structure 2: A thick construction, comprising:
120 mm bituminous layer on
300 mm of crushed aggregate

Structure 3: A semi-rigid construction, comprising:
60 mm bituminous layer on
180 mm of crushed aggregate
bound with cement

Each of these structures was constructed on the in-situ subgrade, whose strength was assessed as 5-7% CBR.

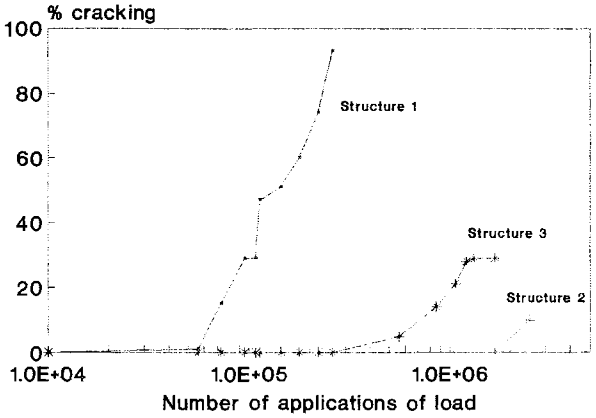

Fig. 2. Development of cracking under 11.5 tonne axle load

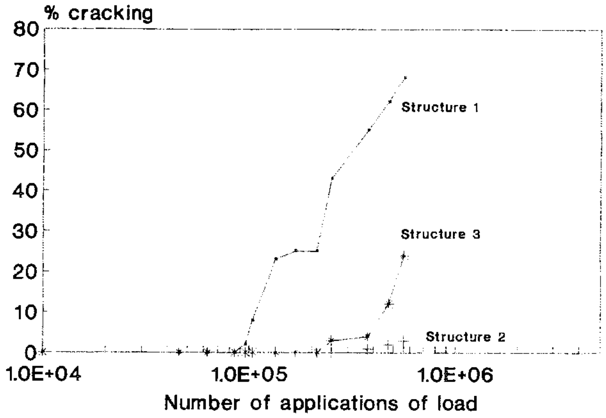

Fig. 3. Development of cracking under 10 tonne axle load

General behaviour of the pavements

a) Cracking of the various structures.

A comparison of the behaviour of each of the sections is most easily made from the semi-logarithmic presentations of Figures 2 (11.5 tonne axle) and 3 (10 tonne axle). Initially, little cracking was observed under the application of many wheel loads. Cracking then began to proceed at a more noticeable rate. For the fully flexible pavements, cracking proceeded according to an exponential relationship with the number of applications of the wheel load; for the structure containing the cement bound layer, this relationship was less well-defined.

b) Rutting of the various structures.

At regular intervals throughout the test, the transverse profile of the pavements was measured. From these measurements, the maximum rut depth was calculated. Figures 4 (11.5 tonne axle) and 5 (10 tonne axle) show the development of rutting (as represented by the maximum rut depth) plotted on a semi-logarithmic scale against the number of wheel loads.

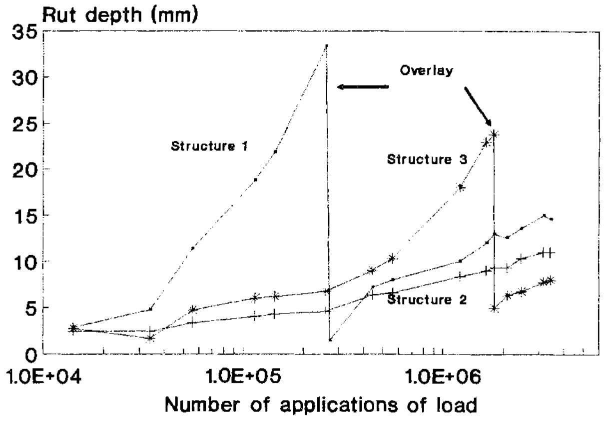

Fig. 4. Development of rutting under 11.5 tonne axle load

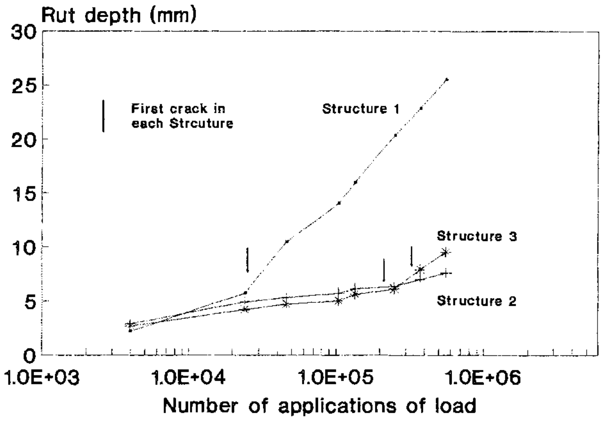

Fig. 5. Development of rutting under 10 tonne axle load

The pavement wear effects of 10T and 11.5T axle loads

The facility was able to load pavements simultaneously with two axle loads by setting the radius of rotation of two of the four loading assemblies to a different value (16 metres) from that of the remaining two (19 metres). This provided a valuable opportunity to directly compare the relative effects of the loads on the pavement. The proposed new axle load limit of 11.5 tonnes for driving axles within EC member countries was selected as the reference axle load in the FORCE test and the 10 tonne axle load was selected for comparison. The 11.5T axle load was used on the outer ring (Sections O1 [Outer ring, Section 1], O2, O3), where the radius of rotation was 19 metres, and the 10T axle load for the inner ring (Sections I1 [Inner ring, Section 1], I2, I3), on a 16 metre radius. Cracking and rutting of the pavements were used as the principal performance indicators for comparison of the effects of different wheel loads.

Trafficking under each wheel load continued until Structure 1 (Sections O1 and I1, bituminous layers 60 mm thick) had reached a failure condition and it was possible to estimate the relative wear effects of the two axle loads. By the end of this phase sections O3 and I3 of the structure 3 (cement treated road base course) had also cracked, although to different degrees, again allowing relative wear effects to be estimated.

Relative rutting due to different axle loads

Full-scale test facilities in a number of countries have frequently been used to investigate relationships between pavement performance, axle loads and the number of load applications. Some of these tests have provided valuable information which can be used as a basis for the present analysis. For example, a total of 48 tests at the Bundesanstalt fur Strassenwesen (BaSt) in Germany have led to the formulation of a law to describe permanent deformation (rutting) as a function of the number of load-repetitions.

Following a phase of consolidation of the paving material at the beginning of each test, the rate of rutting becomes dependent on the number of applications of the load. The exponent in this law, describing the dependence of rut depth on the number of applications of the load, was found to be 0.5 ± 0.2 in 90 % of the tests carried out.

Table 1 summarises the results of an analysis of the relative wear effects using the approach detailed in the full report of the experiment (OECD 1991). In the analysis, it was assumed that relative wear effects of the two axle loads would be described by an exponential law, with exponent "p"; conventionally, therefore, "p" would have the value 4. In the analysis of the FORCE experiment on the basis of rutting, however, the dependence of "p" on pavement strength is clear from the results presented.

TABLE I
SUMMARY OF POWER LAW EXPONENTS ON THE BASIS OF RUTTING

Structure Type	Exponent, p, in power law
Structure 1 Thin bituminous	5.7
Structure 2 Thick bituminous	2.9
Structure 3 Cement treated	1.5

Relative cracking due to different axle loads

When pavements deteriorate by cracking it is possible to indicate the intensity of deterioration in one of two ways. Intensity of cracking may be expressed as either the total length of cracking in a fixed length of pavement, or as that area of pavement observed to be cracked expressed as a percentage of the total area of pavement.

In the FORCE test, although cracks may proceed in virtually any direction, the overall length in the direction of wheel travel, plus 25 cm on each side was taken to be the extent of cracking: the length of a purely transverse crack was thus 50 cm. The total length of cracking was divided by the length of the test section, to give the percentage, which was used as the principal measure of cracking. No index of severity was used in the assessment,but cracks were characterised as either transverse, longitudinal or diagonal.

Using the definitions above, and the observations made in the experiment, the relative wear effects of axle loads can therefore be assessed on the basis of either the area of cracked pavement, or the total length of cracking.

a) based on cracked area

The percentage of cracking observed in the FORCE test, expressed as a function of the number of load applications is shown in Figure 6.

The principle for comparison of the relative effects of the two loads is that the number of load applications bringing about the same defined degree of cracking for each load is noted, allowing the appropriate exponential law relating deterioration to axle load to be calculated. The value of the exponent "p" in this law has been calculated for different levels of deterioration and is shown in Figure 7 to vary between 1.80 and 6.68; the value of the exponent follows a broadly linear relationship with the percentage of cracking observed.

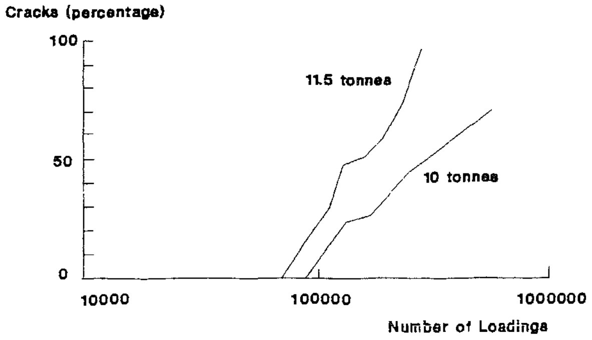

Fig. 6. Development of cracking in Structure 1

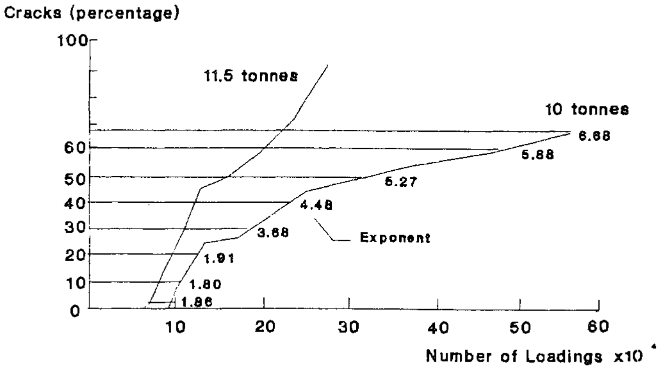

Fig. 7. Derivation of exponents based on cracking percentage

b) based on total crack length

The total crack lengths were divided by the length of the section and later expressed as crack length / 100 linear metres. Figure 8 illustrates the relationship between crack length and the number of load applications. The corresponding values of the exponent were calculated in the same way as above and the results are presented in Figure 9. In this case, values vary from 2.40 to 8.85, increasing linearly up to about 400 000 applications and becoming less linear beyond this figure.

Deterioration in the FORCE test was expressed primarily as the total length of cracking in relation to the length of the section (as a percentage), and this does not correspond directly to criteria used in most countries. However, a 25-30 per cent degree of cracking in the FORCE experiment is roughly equivalent to 60 - 100 crack metres per 100 linear metres of road, (a more common intervention value in many countries). At this level, the exponent values would be 3.2 - 3.7 based on cracked area and 2.7 - 4.3 based on cracked length.

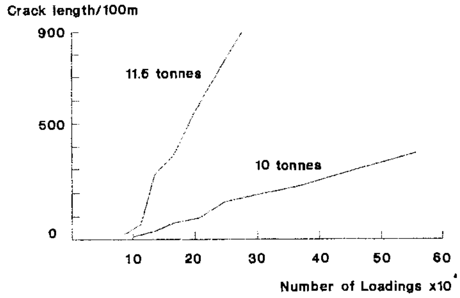

Fig. 8. Development of total crack length of Structure 1.

COMPARISON WITH EXISTING WEAR RELATIONSHIPS

As noted earlier, the most widely-used relationship between applied load and pavement wear is that derived from the AASHO Road Test.

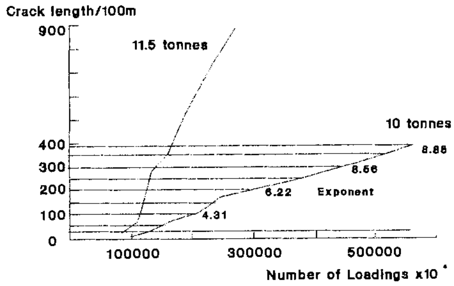

Fig. 9. Derivation of exponents based on crack length

The results obtained from the FORCE experiment broadly confirm this relationship but indicate also the potential for variations in the 4th power law according to pavement strength and the definition of structural deterioration. Variations tend to be greater for deterioration by cracking than for rutting, due to the fact that deterioration was allowed to proceed much further in the experiment than would be allowed in practice. When more practical intervention levels are considered, the deterioration relationship is very similar to that from the AASHO Road Test.

The departures from a single law observed in the OECD test may be significant in some situations. Where cracking is a principal criterion of deterioration, it is probable that the fourth power law is sufficiently robust for design purposes, particularly when deterioration is not allowed to proceed too far beyond normal intervention levels. In the case of rutting, however, the dependence of the relationship is on the strength of the pavement considered rather than the degree of pavement deterioration, and this could lead to more serious difficulties for the design engineer. The departures will, in any event, require further confirmation from a somewhat wider range of pavement constructions than was investigated in FORCE.

3. THE EFFECT OF AXLE CONFIGURATION

In the UK, because of the need to protect highway bridges, Vehicle Construction and Use Regulations (1978) impose a progressively tighter restriction on an individual axle weight as axle spacing is reduced in a two or three axle bogie. For these, the criterion was that a change in axle load, number or spacing should not result in a higher calculated bending moment and shear stress than would be obtained from the then existing design loading.

In a road pavement, deformation and other physical wear is dependent on the stress and strain distributions generated within the structure by rolling wheels. Whilst these distributions interact for closely spaced axles, their complexity, and the properties of the materials involved, imply that addition of strains due to axles in a bogie does not always take place. Present pavement design methods do, however, set criteria for the two principal modes of deterioration, namely wheeltrack rutting or deformation, and cracking. These criteria are based on the vertical strain in the soil or subgrade, and longitudinal strain at the underside of the road base.

There have been a number of studies of the interaction of the stresses and strains generated by tandem or triple axles. In the UK, the most recent of these has been that conducted by Robinson (1989). Tests were carried out on a single pavement construction to assess the effects on pavement strain of different axle and wheel configurations. The strain criteria noted above were then applied to estimate the likely consequences for road wear. Figure 10 shows typical pavement strain measurements recorded during the passage of a 5-axle articulated vehicle. The parameters of interest are the peak

Average build-up of deformation per pass of a tandem or triple axle compared with that of a single axle.

Axle spacing (m)	Wheel type	Tandem axle	Triple axle
Estimates derived from maximum peak strain:			
1.35	Single	1.01	1.05
1.8	Dual	0.74	--
Estimates derived from all peak strains:			
1.35	Single	1.51	2.06
1.8	Dual	1.24	--

TABLE 2

EFFECTS OF AXLE GROUPINGS ON DEFORMATION IN THE SUBGRADE

Average loss of fatigue life per pass of a tandem or triple axle compared with that of a single axle.

Axle spacing (m)	Wheel type	Tandem axle	Triple axle
Estimates derived from peak strain values:			
1.35	Single	--	0.45
1.35	Dual	0.51	0.35
1.8	Dual	0.74	--
Estimates derived from values of the full tensile-going strain:			
1.35	Single	--	0.82
1.35	Dual	0.72	0.68
1.8	Dual	1.04	--

TABLE 3
EFFECTS OF AXLE GROUPINGS ON PAVEMENT FATIGUE

strain levels, and the differences in level between strain peaks and preceding minimum values. Tables 2 and 3 summarise the results of these experiments as high and low estimates of the relative effects on deformation and fatigue of the pavement, for axle loads close to the maximum permitted for each of the axle configurations used. For fatigue effects, both the high and low estimates show that the effects of grouped axles, calculated from the measured strains, are generally appreciably lower than the corresponding effects of single axles. Although the difference may be small, the results also suggest that triple axle groups cause less loss of fatigue life per pass than axles in tandem groups.

When the deformation criterion is considered, however, the closer spaced tandem axle group is apparently more severe than the single axle; at the wider spacing the effect is much less apparent. The results again suggest that the effects of grouping are more extreme for triple axles than for tandem axles.

The results of these tests are indicative only, and more experimental verification on different pavement types is required to provide definitive values.

Limited comparisons can, however, be made with the results of the AASHO Road Test, in which the effect of tandem axles was also considered. In the AASHO test, although the criteria for pavement wear were different, the average loss of pavement serviceability per pass of a 1.3 m spaced tandem axle was 70% of that due to a single axle carrying the same load.

4. THE EFFECTS OF WHEEL (TYRE) TYPE

Many analytical methods for the design of road pavements require as one of their inputs an estimate of the contact area between the tyre and road pavement as well as the magnitude of the applied load, in order to establish the contact pressure.

For many years, both rigid and articulated vehicles were often equipped with dual wheel arrangements on axles other thsan the front steer axle. Recently, the use of the wide-base single (or super single) tyre on such axles has become more common.

Studies were carried out at TRL to investigate how changes in tyre type or tyre pressure may affect pavement wear. The tests were conducted in the TRL Pavement Test Facility, in which controlled wheel loads are applied to full-scale experimental pavements.

The bituminous pavements were kept at a constant temperature of 20°C at a depth of 40 mm. The test wheel travelled at 20 km/h over the pavement test section, and measurements of the principal strains generated in the pavement were taken under a wheel load of 40 kN with the wheel at a range of lateral displacements from the pavement centre line of up to ± 0.5 m.

The results of these experiments are summarised in Figures 11 and 12. The use of the super single tyre rather than the dual wheel arrangement was found to increase the two principal strain measurements in the relatively thin pavement tested by about 50%.

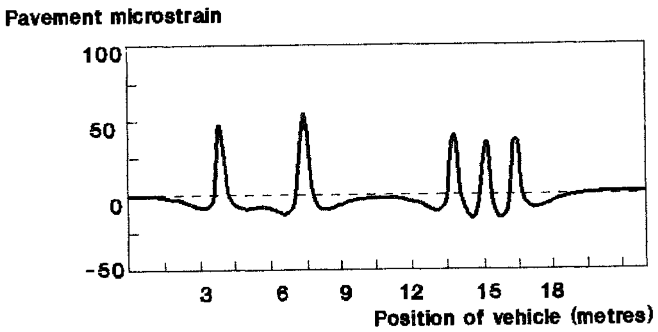

Fig. 10. Pavement strains under a 5-axle articulated vehicle

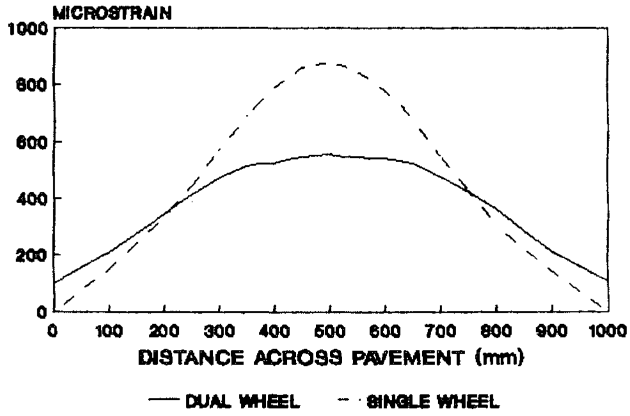

Fig. 11. Average subgrade strains under single and dual wheels

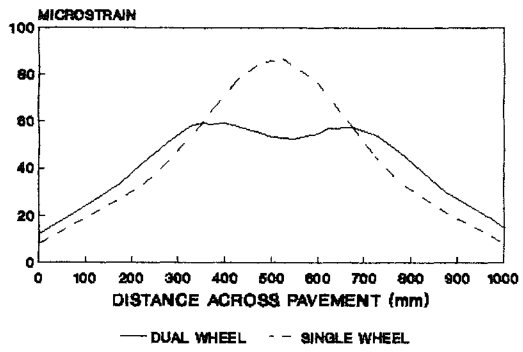

Fig. 12. Average base strains under single and dual wheels

In order to examine the possible effects on thicker pavements, a theoretical analysis was carried out using a model of pavement response to imposed wheel loads. In the analysis, calculations were limited to estimating the relative fatigue effects of single and dual wheels using recommended values for material properties given by Powell et al (1984). The results of this analysis, over a range of pavement thicknesses, are shown in Table 4. For the thickness of Dense Bitumen Macadam used in the experimental work, 150 mm, the calculated relative fatigue effect of single and dual wheels is 2.05. This compares with the experimentally derived figure of 2.5. The difference between these two figures is not, however, statistically significant, and the results in Table 4 may therefore be used as a guide to the relative effects of the two wheel arrangements at greater pavement thicknesses.

Increases in pavement wear due to changes in tyre pressure over a wide range were found to be smaller, but still substantial. A 40 psi increase in tyre pressure, in the range 60 - 140 psi, would increase pavement wear due to fatigue by a factor of 1.26.

DBM thickness (mm)	Ratio of wear Single : Dual
150	2.05
175	1.90
200	1.80
225	1.71
250	1.63
275	1.56
300	1.53

TABLE 4
EFFECTS OF PAVEMENT THICKNESS ON RELATIVE FATIGUE LIVES DUE TO SINGLE AND DUAL WHEELS

5. SUSPENSION SYSTEMS

Present UK methods for pavement design and maintenance take account of only the static axle weights of all heavy goods vehicles. However, it is known that as a heavy vehicle passes over a pavement, the loads applied are affected by the type of suspension and the longitudinal profile of the pavement.

In recent years there has been a considerable expansion of research in this field, beginning with the work of Dickerson and Mace (1981) in the UK, and Sweatman (1983) in Australia. On the assumption that reduced dynamic loading will be beneficial to pavement life, this effort has frequently been directed towards improved understanding of the effects of various vehicle parameters on the loading imposed on the road pavement. In contrast, relatively few attempts have been made to quantify the effects of dynamic loading on pavement life and the consequential costs for road maintenance.

Eisenmann (1975) derived a "road stress factor", or dynamic pavement wear factor, using the assumption that road wear depends on the fourth power of the instantaneous wheel force. For a Gaussian distribution of dynamic wheel forces, Eisenmann showed that the dynamic pavement wear factor (DWF), indicating the excess of wear under dynamic loading conditions compared with "static" loading of the pavement, is defined as:

$$DWF=1+6(dlc)^2+3(dlc)^4$$

where dlc = Coefficient of variation of dynamic tyre force on the pavement

Sweatman (1983), Hahn (1987) and Mitchell and Gyenes (1989) used this approach to assess the additional structural wear on pavements due to dynamic loading. The smallest estimates of this wear were obtained by Mitchell and Gyenes (1989), who suggest that overall wear on pavements by semi-trailer axles could be reduced by up to 20% as a result of the replacement of steel and rubber suspensions with air suspensions. Partly for this reason, regulations in the UK, Sweden, Belgium, and elsewhere now permit a small load premium to vehicles having air suspension.

While the road stress factor approach developed by Eisenmann permitted a much improved understanding of dynamic pavement behaviour, the effects of more recently investigated parameters should also be taken into account. Whereas Eisenmann assumed that dynamic loads are applied as a series of discrete single axles, Mitchell and Gyenes (1989) have noted the possible dynamic interaction of groups of axles. Furthermore, although Eisenmann assumed that wear takes place randomly over the surface of the pavement, Addis et al (1986) have shown the potential for an accumulation of peak dynamic loads at or near specific features of a longitudinal profile.

Much of the UK Motorway and trunk road network employs pavements of fully flexible construction. These materials have a response to loads which is a function of the frequency of the applied load and of the intervals between loadings. Recent unpublished work at TRL, for example, indicates a very strong dependence of calculated pavement life on traffic speed (the analogue of frequency of applied loading). Laboratory measurements indicate that the stiffness of a bituminous material reduces as the loading frequency decreases, so that bituminous layers may become less effective at spreading wheel load stresses as traffic speeds become lower. In practice, however, roads appear to behave adequately over a range of normal traffic speeds, and there is little evidence to suggest that the practical effect for normal slow moving traffic is as great as theory suggests.

Few of the current models of pavement response and performance include the effects of moving loads, or the damping effects of viscoelastic materials. Dynamic loading of a pavement takes place at several different frequencies, with variable intervals between loads, and a more appropriate and reliable method of assessment of pavement wear requires the development of an improved model taking these into account. Some progress has been made in the development of such models, (Hardy and Cebon 1988, Hardy 1990 for example), but these are not yet completely validated over the wide range of both truck types and pavement designs encountered in the UK and elsewhere. In order to bring about further progress in this area, the Organisation for Economic Cooperation and Development (OECD) is proposing to carry out an experiment involving the collaboration of many different countries.

6. CONCLUSIONS

1. For most purposes, the fourth power law relating structural wear in pavements and wheel load is adequate; the results of the recent FORCE experiment indicate that departures may arise when considering a wide range of pavement strengths, or the nature and degree of the deterioration.

2. Measurements in a pavement under traffic indicate that the effects on pavement life of axle configuration differ according to whether fatigue or deformation criteria are considered. In general the results show that the effects of grouping are greater for triple axles than for tandem axles.

3. Measurements of the effect of wide single tyres, compared with the dual-tyre arrangement, show an increase of approximately 50% in the two principal strain measurements generated in a relatively thin pavement. This increases pavement wear, in the case of fatigue, by a factor of up to 2.5. Theoretical analysis of the effects on thicker pavements indicates that the factor will lie in the range 1.5 - 1.8 for those pavement thicknesses commonly used for carrying heavier traffic in the UK.

4. Although much is known about the effects of different vehicle parameters on the magnitudes of loads imposed on road pavements, the effects of these varying loads at varying frequencies and on changing longitudinal pavement profiles is less well understood. Further work is necessary on the prediction of the effects of interaction between longitudinal pavement profile, the vehicle, and the consequent pavement wear resulting from the applied dynamic loading.

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