The influence of road profiles on pavement wear

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ABSTRACT

In order to examine the effect of road unevenness on the dynamic loading applied to a pavement, the Transport Operations Group (TORG), supported by funding from West Yorkshire Metropolitan County Council and Science and Engineering Research Council, and in collaboration with the Transport and Road Research Laboratory have established a test laboratory within a private haul road. Resistance-foil strain gauges have been located at the under-side of the road base to measure the transient horizontal radial strain at 0.5 m centres under each of the two wheel-tracks as vehicles travel over the 30m test section. Each of the strain gauges was calibrated using an instrumented 2-axle, 16 tonne, heavy goods vehicle. The calibrated strain gauges were then used to monitor the dynamic loading characteristics of two large Dump Trucks used on the site. Relationships were developed between the dynamic load coefficient, road unevenness and speed for each of the axles on the test vehicles.

1. Background

Annual expenditure on the construction and maintenance of highways in the United Kingdom is in excess of £4 billion. Even small refinements to the design, maintenance and cost allocation procedures can result, therefore, in significant savings when considered in absolute terms.

The structural wear of road pavements is attributed primarily to the cumulative effect of wheel-loads passing over the pavement surface. Current UK design procedures relate the degree of wear to the fourth power of static axle weight. In recent years, however, attention has been focussed on the possible contribution of dynamic loading to overall structural wear; possible refinements to vehicle suspension design procedures could result in a smaller component of dynamic loading, and thus lead to lower pavement wear.

The work described in this report arises from this background and aims to investigate the mechanism and magnitude of the dynamic loading of road pavements with particular reference to the effects of changes in the unevenness of the road.

2. Previous Work

Attempts have been made to understand the dynamic interaction between wheeled vehicles and road surfaces since the mid-1970s. It has been established that when a vehicle travels along a road, at any speed above 'creep speed', it bounces on its tyres and suspension causing the axle-loads to fluctuate above and below their average static weights. The sum of these dynamic axle-loads at any point in time will not generally equal the static weight of the vehicle; the dynamic component to each of the static wheel-loads as they progress along the road surface causes the vehicle or, more
particularly, the unsprung masses, (e.g. the axles, wheels, hubs and tyres) to accelerate vertically.

Page (1976) measured the dynamic wheel-loads exerted by a 2-axle rigid goods vehicle on a number of bridge decks, to establish a dynamic factor to apply in design.

In the late 1970s, Dickerson and Mace (1981) measured the dynamic wheel-loads on a 2-axle rigid vehicle, at various speeds over sections of public road, using a vehicle-mounted system in which the vertical deflection of the tyres was used as a measure of the instantaneous wheel-load. They showed that the vehicle running on a smooth road had wheel-loads that were fluctuating continuously at about 3Hz with the spring suspension scarcely moving. The amplitude of the dynamic wheel-load on any one section had a Gaussian distribution to at least two standard deviations. The standard deviation of the dynamic loads increased with increasing speed and road unevenness; at a speed of 64 km/hour on main roads it ranged from 0.1 to 0.3 times the static wheel-load. Also, the effects of tyre pressure, tyre type and wheel-load were examined.


Addis et al (1986) transferred the instrumentation system developed by Dickerson and Mace (1981) to a 2-axle semi-trailer. The trailer was driven over a length of test track in which strain gauges had been installed and, also, on public roads. The standard deviations of the dynamic loads were found to be similar to those previously reported by Dickerson and Mace (1981). Also, when repeated passes were made over the test section at a set speed, the locations of the minimum and maximum dynamic wheel-loads remained constant for each pass and the peak amplitudes varied between passes by between 10 and 20 per cent. The repeatability of the results suggests that the road unevenness must influence the amplitude of the dynamic wheel-load profile and the locations of the maximum and minimum wheel-loads.

Furthermore, Addis et al reached a number of other important conclusions.

i) Dynamic loading of the test pavement was brought about by the vehicle bouncing on its tyres, at a frequency of 3 Hz. This was a lightly damped movement excited by small variations in road unevenness and out of balance forces on the vehicle such as might be expected on a high-speed principal road built to normal United Kingdom standards.
ii) On a road having good unevenness characteristics, dynamic loads up to ± 15 per cent of the nominal static axle-load were recorded for tandem axles. For a single axle trailer the dynamic component was ± 25 per cent.

iii) These variations in loading were accompanied by measured variations in stress and strain in the pavement of up to ± 20 per cent of that expected for the nominal static load. It was calculated that the consequence of the increased strain at the under-side of the roadbase could be to reduce the life of particular areas of some pavements by up to 50 per cent.

iv) An additional component of dynamic loading, induced by long wavelength variations in pavement, caused an increase of 19 per cent in the rear trailer axle-load on a smooth pavement. This was attributable to the inadequacy of the mechanism for sharing load between the two axles of the semi-trailer.

v) These results were obtained from one vehicle operating over one pavement. Further measurements on a range of vehicle/suspension types would be needed before conclusions of more general applicability could be drawn.

Mitchell (1987) monitored instantaneous wheel-loads, using strain gauges to measure axle-bending between the wheel-hubs and spring attachments. Accelerometers on the hubs enabled allowance to be made for inertia loads brought about by the masses between the strain gauges and the tyre contact patch. Spring movement was measured using displacement transducers and movements of the sprung mass with accelerometers. This work concluded that all road vehicles bounce on their tyres and suspension, and that the these dynamics are mainly excited by road features. The amplitudes of the increased loads were randomly distributed with a standard deviation, on a good smooth main road at a speed of 64 km/h, that was typically 10 to 20 per cent of the static load.

Mace and Stephenson (1989) investigated the fluctuations in the dynamic wheel-loads applied to the road surface by a two-axle semi-trailer fitted with mono-leaf spring suspension. Dynamic wheel-load was assessed by measuring the deflection of the tyre, using a laser-based contactless sensor. The dynamic load coefficient (i.e. the ratio of the standard deviation of the dynamic load to the static load) was used as a means of quantifying the dynamic variation of wheel load.

The dynamic load was seen to be a significant component of the total load; the dynamic load coefficients ranged between approximately 0.05 and 0.15 for a laden trailer and between approximately 0.05 and 0.20 for an unladen trailer.

It was found that the dynamic load coefficients due to the offside and nearside wheels were approximately equal for any given run. A positive linear relationship was found to exist between the dynamic load coefficient and the mean of the offside and nearside road unevenness for a given section. This was more marked than the relationship between the dynamic
load coefficient and the road unevenness for an individual wheel-track, and so road unevenness was defined as the mean of the offside and nearside unevenness. The linearity was less well defined for road unevenness values between 1.25 mm and 1.75 mm, particularly when the trailer was unladen.

The dynamic load coefficient was higher at 32 km/h than at 64 km/h for small values of road unevenness when the trailer was unladen, but was higher at 64 km/h than at 32 km/h for large values of road unevenness whether the trailer was laden or unladen.

Dynamic pavement loads were measured for a variety of truck suspensions, in work described by Mitchell and Gyenes (1989), using vehicles equipped with strain gauges and accelerometers to monitor instantaneous wheel-loads while the vehicles travelled along the sections of road under investigation.

At all speeds and on sections of road having varying unevenness, air sprung semi-trailer bogies produced lower dynamic loads than steel leaf sprung bogies, while rubber spring bogies produced dynamic loads that were always higher than those for air bogies, and usually higher than those for steel sprung bogies. Three-axle bogies usually produced lower dynamic loads than two-axle bogies. Steel leaf semi-trailer bogies generated higher dynamic loads than steel leaf tractor drive axles, leading to reduced differences in pavement wear between lighter trailer axles and heavier drive axles.

The measurements showed that loads applied to roads by heavy goods vehicles could be reduced significantly, perhaps by 10 to 15 per cent, if all goods vehicles were fitted with the suspension system offering the most favourable dynamic characteristics.

Much is, therefore, known about the effects of a number of vehicle parameters on the degree of dynamic loading that occurs in practice. Relatively little, however, is known about the effects of road unevenness on dynamic loading, and there have been no attempts to quantify by measurement the relation between deterioration of unevenness and dynamic loading. If such a relationship could be established, and a model of the deterioration of unevenness existed, the possible consequences of dynamic loading over the whole of the life of the road could be assessed.

3. Pavement wear aspects

Two main modes of structural failure are associated with flexible road pavements:

(i) a gradual build-up of permanent deformation (i.e. rutting) observable at the surface in the wheel-tracks; and

(ii) the development of cracks in the surface.

A structural failure due to wheel-track rutting is generally attributed to the accumulation of residual transient vertical
compressive strain induced by the traffic, producing permanent deformation in the subgrade, which is reflected in each of the pavement layers above. In the UK, the pavement is deemed to have reached a critical condition when the rut-depth on the surface has reached 10 mm. A fatigue failure is assumed to occur when the transient horizontal tensile strain at the bottom of the base layer eventually produces cracking which propagates up to the surface. Such cracking will normally appear within the wheel-tracks and is the alternative criterion for pavement failure.

In the UK, for flexible roads, the pavement design process allows for failure by both fatigue and rutting. The importance, therefore, of the characteristics of the transient horizontal strain at the bottom of the base of the pavement is clear and the consequences are related directly to both pavement design and maintenance procedures.

Recorded attempts to correlate measured dynamic axle-loads with the respective measured levels of base strain have been by Addis et al (1986) and Gorge (1984), as discussed in Section 2. The research was limited to the passage of one instrumented vehicle, operating over a particular section of road, with strain gauges that had been installed at the base/sub-base interface. The number of strain gauges was limited but the results showed that the level of strain varied by up to ± 20 per cent of the level that would be expected for the nominal static load. Based on conventional relationships between applied load and wear, the consequence of this increased strain could be to reduce the life of particular areas of some pavements by up to 50 per cent.

For the present work it was decided to extend that of Addis et al (1986) by constructing a test pavement with a more comprehensive system of pavement strain gauges that could be used to monitor the structural effects of the passage of any vehicle passing over the test section at a range of speeds. Each strain gauge would be calibrated using dynamic wheel-load data from an instrumented, 2-axle heavy goods vehicle. Using this calibration, it would be possible to monitor the instantaneous dynamic wheel load of any vehicle, at any point along the wheel-tracks of the test section.

Three main objectives were envisaged:
(a) to establish relationships (if any) between speed, dynamic wheel-load, pavement strain, pavement wear and unevenness for a 2-axle instrumented heavy goods vehicle;
(b) to establish relationships (if any) between pavement strain, pavement wear and unevenness for other heavy vehicles; and
(c) to assess the implications of objectives (a) and (b) for pavement design and the allocation of road track costs.
4. Experimental Design

4.1 Overview

From the previous work described earlier, it was clear that the key variables would probably be:

i) the characteristics of the suspension system and tyres;
ii) the mass of the vehicle;
iii) the speed of the vehicle; and
iv) the unevenness of the road.

Also, the expected dynamic loads comprised:

(i) a quasi-static load representing the static load adjusted to allow for the long-wavelength profile of the road;
(ii) an additional sinusoidal load, which would have been generated even if the road surface had been perfectly smooth, due to the tyre and rim eccentricities; and
(iii) a further component due to the unevenness of the road.

The test site (described in Section 4.2) was used for the investigation and vehicle types were limited to an instrumented 2-axle, 16 tonne Volvo heavy goods vehicle on loan from TRRL and two Aveling Barford LD55, 3-axle, rigid dump trucks which formed part of the fleet of haul vehicles.

In this way, the variables were confined to

i) two types of vehicle;
ii) the speed of the vehicles; and
iii) the unevenness of two wheel-tracks.

The dynamic wheel-loads of both types of vehicle were monitored for a range of vehicle speed. The unevenness was measured using the TRRL High Speed Road Monitor (Jordan and Cooper, 1989). Using these data, an attempt was made to identify the characteristics of the dynamic loading of road pavements.

4.2 Establishing the Site

In response to the report of the Flowers Commission (HMSO, 1981), the Department of the Environment (DoE) agreed to finance capital works on several demonstration projects associated with the disposal of colliery spoil. In 1986, the then West Yorkshire Metropolitan County Council (WYMCC) were granted £1.5 M from this source to finance a 2.5 km length of private experimental haul-road that will be used, over the next forty years, to reclaim 500 ha of mainly derelict land at Welbeck in the Calder Valley to the east of Wakefield.

The haul-road is used to convey spoil by lorry from the Sharlston Colliery to the Welbeck site. The number of return
journeys per day was not expected to exceed 140, involving up to six 30 tonne Aveling Barford dump trucks. The haul-road was designed to be 8 m wide with a 3 m verge each side.

Academic institutions throughout UK were invited to submit bids for research, demonstration and monitoring activities associated with the disposal of spoil from the Sharlston Colliery. As a result, funds were allocated to the Transport Operations Research Group (TORG) at the University of Newcastle upon Tyne towards the cost of instrumenting a length of the haul-road to investigate the dynamic loading of road pavements. The Science and Engineering Research Council (SERC) contributed further funds and under a collaborative research agreement with the University the Transport and Road Research Laboratory (TRRL) offered advice and assistance in the design, construction and execution of the experiment.

The instrumented pavement comprised 45 mm of hot rolled asphalt wearing course and two, 90 mm, layers of dense bituminous macadam roadbase on a 240 mm DTp Type 1 sub-base. The naturally-occurring subgrade was a weathered sandstone which, when exposed, proved to be too strong and unsuitable for the installation of the instrumentation. The subgrade under the test section was duly excavated to a depth of 600 mm and replaced with a suitable clay material. The imported subgrade produced a 7 per cent surface CBR value, which was considered to be a satisfactory foundation for the sub-base, and gave a material suitable for the installation of strain gauges.

The test facility was completed in April 1987; details of construction and layout are given in Figures 1 and 2, and Plate 1 shows a general view of the completed site. The haul-road was instrumented between Ch 8 + 55 and Ch 8 + 85 under the westbound lane (i.e. Sharlston to Welbeck) with 120 ohm resistance-foil strain gauges located at the bottom of the road-base. These were intended to measure the transient horizontal longitudinal strain at 0.5 m centres under each of the two wheel-tracks, involving a total of 126 strain gauges in all. Seventy per cent of the gauges survived the construction process which was sufficient for the future work programmed for the test facility.

4.3 Site Characteristics

Throughout the test pavement construction, three characteristics of the site gave rise to considerable difficulties:

(i) The site was in a ten-metre deep cutting and, although filter drains had been incorporated along the toes of the cutting slope, water from the surface appeared to be affecting the performance of the strain gauges.

(ii) The clay subgrade was an artificial imported subgrade. The naturally-occurring subgrade was a weathered sandstone which lined the edges and base of the imported clay subgrade. Any water penetrating the pavement in
some way, could become trapped and affect both the durability of the pavement and the performance of the strain gauges.

(iii) The main cross-Pennine overhead power lines conveying electricity from Ferrybridge Power Station to Lancashire were located adjacent to the site generating a dominant electrical noise in the immediate environment, at a frequency of 50 Hz.

A great deal of development work was necessary to overcome earth leakage and a noise level that dominated the signals from the strain gauges. The successful system which was developed finally is shown as a block diagram in Figure 3.

4.4 Details of the Test Vehicles

(a) The Instrumented Vehicle

(i) Specification:

Type: 2-axle rigid Volvo F88 "extended tractor unit"

Plated weights: 16.26 tonnes (gross)
10.0 tonnes (rear axle)

Outboard mass: 0.345 tonnes (rear)
0.187 tonnes (front)

Wheel base: 4.905 m

Wheel track: Front (single tyres): 2.04 m
Rear (dual tyres): 1.84 m

Suspension: Steel leaf springs (drive axle has many leaves and is exceptionally stiff)

Tyres:
Front: 11.00 R 20 Michelin XZA
Rear: 10.00 R 20 Michelin X

(ii) Description:

This vehicle was developed by TRRL and was loaned to the project for one week. The vehicle was instrumented to measure all wheel loads simultaneously, by using strain gauges to measure the bending of the axles between the suspension and the hub together with accelerometers to correct for the vertical inertia loads due to the unsprung mass outboard of the strain gauges. Signals from these sensors were recorded on analogue magnetic tape. A locational referencing system, which was synchronised with the on-board data collection system was provided by counting automatically revolutions of the prop-shaft. The start of the test section was marked by a reflective strip on a stake at the side of the road which returned a light beam to a photocell on the vehicle. This system located the vehicle on the test section to an accuracy of about ± 100 mm. The load measuring instrumentation was probably accurate to ± 3 per cent at 3 Hz and ± 5 per cent at 15 Hz, although this was difficult to establish experimentally. Plate 2 shows the instrumented vehicle driving down the test site, with its offside wheels aligned over the offside line of gauges.

(b) Dump trucks

(i) Specification;
Type: 3-axle rigid Aveling Barford LD55
Plated weights: 25.61 tonnes (gross)
19.56 tonnes (rear bogie)
6.10 tonnes (front axle)
Wheel base: 3.861 m (front to leading bogie)
1.398 m (bogie wheels)
Wheel track: 1.905 m
Suspension: Semi-elliptic leaf springs
Tyres: 11.00-22 14 PR single (front)
15.00-20 20 PR single (rear)

(ii) Description:
The fleet of haul vehicles using the road comprised Aveling Barford LD55 and Haulamatic 615 dump trucks. Two of the Aveling Barford LD55s were selected for use in the project and these were labelled so that they were visible as they approached the test length. The geometric characteristics of the site restricted the speed of the dump trucks and prevented data being gathered above a speed of 50 km/h. Plate 3 shows an example of the dump truck in operation.

4.5 Calibrating the Strain Gauges

Section 4.2 described the number, location and type of strain gauges that were installed under the wheel-tracks of the test section of road pavement. For this project, the gauges were to be used to monitor the instantaneous dynamic wheel-loads of the two types of vehicle passing over the test section. The gauges were of the same type but their responses varied widely. There was a need, therefore, to establish, for each gauge, the relationship between vehicle speed, transient strain and the respective dynamic wheel-load generating the strain.

The instrumented test vehicle was used to calibrate the strain gauges. The vehicle was run over the test section at creep speed and at 32, 48, 64 and 80 km/h, with the simultaneous monitoring of the individual dynamic wheel-loads and the respective base strains. This data was then used to establish a relationship, for each gauge, between vehicle speed, base strain and dynamic wheel-load. These relationships were included in the software, so that the instantaneous wheel-loads (relative to that of the calibrating vehicle) of any vehicle could be monitored directly as it travelled over the wheel-tracks.

4.6 The Dump Trucks

The two loaded dump trucks were driven over the test section, at speeds between 45 km/h and 50 km/h, while the base strains were monitored and then converted into continuous s of dynamic wheel-load.

4.7 Road unevenness
The unevenness of the two wheel-tracks were monitored regularly using the TRRL High Speed Road Monitor (HRM), (Jordan and Cooper, 1989), as illustrated in Plate 4.

4.8 Measurement Conditions

(a) Temperature Control

The test pavement comprised base and surfacing materials that were bituminous bound and whose properties, therefore, were susceptible to temperature variations. In this project, strain measurements were recorded only when the pavement temperature was within a temperature range of less than 3°C, the absolute range depending on the pavement depth under consideration. In this way, the effects of temperature were assumed to be not significant.

(b) Transverse position of test vehicle in relation to strain gauges

Care was taken to select a realistic transverse spacing for the two lines of strain gauges, and a central median was constructed to encourage drivers to ensure that the wheels of the test vehicles were directly over the strain gauges during the periods of data collection. The capacity of the data-acquisition equipment permitted the monitoring of only a part of one wheel-track at a time (i.e. up to fourteen strain gauges); it was essential, therefore, to ensure that the wheel-loads being monitored were directly over the respective line of strain gauges to avoid the need to adjust the results for an off-axis loading condition.

(c) Effects of longitudinal gradient

The distribution of the static weight of a vehicle between its wheels will depend on the longitudinal and transverse slopes. The longitudinal profile of the test section formed part of a vertical curve with an average gradient of approximately 3.5 per cent. The effect of the difference in gradient along the test section was not considered significant.

4.9 Work Programme

The following work programme was established:


April 1989: Data collection to enable calibration of strain gauges.


5. DATA COLLECTION

5.1 Instrumented Vehicle: measurement of dynamic loading and base strain

During the week beginning 24th April 1989, TRRL loaned to the project their 2-axle Instrumented Vehicle (see Section 6.2a). The following data were collected with the instrumented vehicle travelling through the test section.

(i) Dynamic wheel load data
Twelve sets of dynamic wheel-load data were collected for each combination of the following variables:
- No. of axles: 2
- Vehicle speeds: creep, 32, 48, 64 and 80 km/h
- No. of wheel-tracks: 2

(ii) Base strain
A minimum of two sets of pavement strain data were collected for each strain gauge under each combination of the following variables:
- No. of axles: 2
- Vehicle speeds: creep, 32, 48, 64 and 80 km/h

(iii) Temperature
Thermo-couples were used to measure the pavement temperature at the surface, 20 mm and 225 mm depth at the beginning, middle and end of the test section.

5.2 Dump Trucks: measurement of base strain

Dump truck data were collected on 17th August 1989 and again on 20th September 1989, when the pavement temperature was similar to the temperatures experienced during the week beginning 24th April 1989. Three sets of the following data were collected for a speed range from 45 to 50 km/h:
- No. of axles: 2
- Nearestide gauges monitored: 30
- Offside gauges monitored: 22

5.3 Pavement unevenness

TRRL measured the wheel-tracks using the High-Speed Road Monitor (Jordan and Cooper, 1989) in June 1987 and June 1989. The data were recorded in digital form, providing an excellent data-base from which to monitor pavement deterioration but, more importantly, for establishing relationships between dynamic wheel loading and road. Figures 4 and 5 compares the two sets of data where the level of any points has been taken as the difference between the height and a 30 m moving average of the , with the difference being taken at the centre of each position of the moving average.

5.4 Pavement Condition

The wheel-tracks within the test section were surveyed regularly to assess the degree of rutting and cracking. Rutting was measured transversely using a 3 metre straight-
edge and wedge; Figure 6 provides information on the development of rutting during the project in each wheel-track.

Table 1 provides information on the development of cracking in each wheel-track during the project period. Since February 1989, there appears to have been no significant increase in cracking. The cracks that had formed at the time were sealed with a clear epoxy sealing agent in November 1987.

5.5 Weather

From the opening of the haul road in April 1987, a comprehensive record has been kept of air temperature, wind speed and rainfall. Initially, this was obtained from the Leeds Meteorological Centre until the on-site recording apparatus became operational in November 1988. Temperature and rainfall statistics are summarised in Figure 7.

5.6 Pavement Loading

Pavement loading data were transcribed from weighbridge records kept by Sharlston Colliery. The variation of the tonnage of spoil conveyed over the test section each week is given in Figure 8; the total tonnage conveyed up to August 1989 was 1.9 million tonnes, at the rate of 0.65 million tonnes per year or 0.17 million standard axles per year.

6. ANALYSIS AND RESULTS

6.1 Calibration of the Strain Gauges

Using the data from the instrumented vehicle, it was possible to compare the peak level of strain developed in the base with the corresponding dynamic wheel load applied to the surface for a range of speeds. Using regression analysis, relationships were developed for each gauge between peak base strain per unit of dynamic load and speed. Figure 9 provides typical examples of these relationships in graphical form and Table 2 lists the relationships developed for each gauge in algebraic form together with the respective correlation coefficients.

These relationships were integrated into the software system enabling the instantaneous dynamic wheel-load of any vehicle to be estimated from the corresponding measurement of base strain. This development enabled continuous dynamic wheel-load to be generated from strain gauge data for any wheel passing along the wheel-tracks. The central median constructed over the length of the test section encouraged the drivers to position vehicles directly over the strain gauges. It is acknowledged that small errors would still be introduced due to lateral drift.
6.2 Spectral Density Analysis

Figures 10, 11 and 12 show the variation of dynamic wheel-load over the test section for each of the wheels of the test vehicles for a range of speed. Each of the figures show the dynamic wheel-loads oscillating about a mean value as the test vehicles pass over the test section.

A spectral density analysis performed on each of the s of dynamic wheel-load is summarised in Figures 13 and 14. For both test vehicles, the results confirm previous findings that each of the wheel-loads oscillated at a frequency of approximately 3 Hz and that this frequency was substantially independent of speed.

6.3 Repeatability of Results

The data were found to be readily repeatable. Figure 15 demonstrates clearly that the same vehicle travelling at the same speed produces minimum and maximum axle-loads at points of common chainage along the test section. Also, it can be seen from the dump truck data (Figure 12) that each of the three axles apply maximum and minimum dynamic loads at points of common chainage for a specific speed. This suggests that even for the atypical test vehicles used in the experiment, pavement unevenness influences both the amplitude of the dynamic load and the chainages along the road where the maximum dynamic load is applied for any particular speed.

6.4 Comparison of Static and Mean Dynamic Wheel Load

The static wheel-loads of the instrumented vehicle were measured using weighpads, to an accuracy of ± 1 per cent. These static loads were compared to the respective mean dynamic wheel loads and the results are given in Figure 16. It is apparent that the ratio of mean dynamic wheel-load and static wheel-load increases with vehicle speed. The difference between the ratio for the nearside and offside wheels was probably due to the crossfall but, even so, at 80 km/h the mean dynamic load of the rear axle was 7.5 per cent higher than the static axle-load. This would produce 34 per cent greater pavement wear assuming the fourth power relationship between pavement wear and static axle-weight.

6.5 Relationships between Peak Dynamic Load, Static Load and Speed

The ratio of the peak dynamic wheel-load of the dominant 3Hz frequency and the respective static wheel load is defined here as the peak load coefficient (PLC). Figure 17 shows the relationship between the PLC and speed for each of the wheels of the test vehicles. The relationships show that the dynamic effect of traffic loading for the test vehicle reaches a peak at a vehicle speed of between 50 and 80 km/h with a corresponding reduction at higher speeds.
6.6 Relationships between Dynamic Load Coefficient, Speed and Unevenness

One of the objectives of the experiment was to attempt to relate deterioration of the unevenness to the magnitude of dynamic loading by making regular and simultaneous measurements of both. This, however, was hindered because satisfactory measurements of strain in the pavement (and by implication the load applied to the pavement) were not possible until some time after the haul-road had been opened to traffic. An alternative approach was therefore developed in which the test section was considered to be three discrete lengths, each having a significantly different unevenness. Pavement strains measured under each of these sections allowed the applied loads to be inferred, and it was then possible to attempt to correlate those loads with measurements of the unevenness. For these purposes the ratio between the standard deviation of dynamic wheel-load and the respective static wheel load is defined here as the Dynamic Load Coefficient (DLC). Road unevenness, R, is defined as the variance of the deviations with respect to a five-metre moving average base level.

Figure 18 shows the relationships between DLC, R and speed, including the regression equation for the set of data. The range of R values was obtained by considering three discrete lengths of each wheel-track. Peak values of DLC varied from 0.070 with an unevenness of 1.26 \( \text{mm}^2 \) to 0.105 with an unevenness of 2.06 \( \text{mm}^2 \); correlation coefficients in the regression were 0.78 and 0.82 respectively.

For each axle on the test vehicle, it was possible to develop a relationship between DLC, R and speed but the limited range of static load and the size and type of tyres and suspension system prevented a general relationship from being developed at this stage. Further work would be necessary to develop a relationship representing the predominant types of heavy goods vehicle operating on the road network. Using such relationships, it would be possible to relate the unevenness of a road surface to pavement wear for a specific traffic flow.

6.7 Implications for Pavement Wear

In order to assess the implications of these results for pavement wear, it is first necessary to consider the most appropriate means of assessing pavement wear due to dynamic loading. As noted earlier, structural wear is related to the fourth power of the static axle-load, and in interpreting the effects of dynamic loading, other workers (for example, Sweatman (1983) and Hahn (1987)) have used this approach.

Although there are grounds for supposing that this may not be the most appropriate method for assessing the effects of dynamic loading, no more suitable method is available at
present and a similar method was, therefore, used in the present work.

Figure 17 shows the relationship between the PLC and speed for each of the wheels of the test vehicles. These imply that the effects of dynamic loading for the test vehicle would be greater for urban roads and low-speed rural roads. Also, as congestion increases on the strategic high-flow rural network, the speed of traffic is likely to decrease and this would probably increase pavement wear. It must be emphasised, however, that similar tests need to be performed using a range of vehicle types and suspensions before any general conclusion could be formed.

Figure 19 summarises the implications for structural pavement wear when the effects of dynamic loading were compared to those that would be expected from static loading for each of the wheels of the test vehicles over a range of speed. The ordinate represents:

\[
\frac{(\text{Peak dynamic wheel-load})^4 - (\text{static wheel-load})^4}{(\text{static wheel-load})^4} \times 100 \%
\]

On a public highway traffic operates at a range of speed and, at any particular point on the wheel-track, individual applied wheel-loads will vary from their minimum to maximum dynamic load depending on their operating speed. To assess the implications of this behaviour, a hypothetical speed distribution was considered:

<table>
<thead>
<tr>
<th>Speed (km/h)</th>
<th>32</th>
<th>48</th>
<th>64</th>
<th>80</th>
</tr>
</thead>
<tbody>
<tr>
<td>Proportion of HGVs (per cent)</td>
<td>10</td>
<td>20</td>
<td>30</td>
<td>40</td>
</tr>
</tbody>
</table>

This distribution was then combined with a traffic flow comprising one hundred passes of the rear wheels of the instrumented vehicle in order to assess the possible effects of different speeds along the test length. Figure 20 illustrates the effect of this hypothetical traffic flow on structural pavement wear, when dynamic loading was compared to static loading. It can be seen that at some locations pavement wear increases by up to approximately 60 per cent for the nearside rear wheel when cumulative dynamic loading is considered.

The work of Addis et al (1986), however, suggested that when similar vehicles travel along a road at the same speed, maximum dynamic loads may occur at points of common chainage, with potentially more serious consequences for pavement life. This is confirmed in Figure 21 which shows the effect of one hundred passes of the instrumented vehicle at a constant speed of 64 km/h; calculated pavement wear increased by up to 100 per cent at certain chainages when cumulative dynamic loading was considered. At this speed, the locations where maximum pavement wear occurred were at approximately 6m centres.
The range of speeds of the dump trucks was small (i.e. from 45 km/h to 55 km/h) and their tyres were very elastic; the consequent pavement wear was, therefore, relatively high. Figures 22, 23 and 24 show that, for one hundred passes of the dump truck wheels, up to a 400 per cent increase in pavement wear was estimated to take place when the cumulative dynamic loading was considered. These peak dynamic loads, which occur at relatively close centres, would be the appropriate value of load on which to base pavement design.

7. CONCLUSIONS

(i) The ratio of mean dynamic axle-load to static axle-load increased with speed. At 80 km/h, the mean dynamic load of the rear axle of the instrumented vehicle was 7.5 per cent higher than the equivalent static load which would lead to an increase of 34 per cent in pavement wear, based on conventional assessment methods.

(ii) The dynamic load coefficient appeared to reach a maximum value at speeds between 50 and 80 km/h. At higher speeds the value decreased, implying that the effects of dynamic loading are greatest for urban and low-speed rural roads, and where congestion reduces normal operating speed.

(iii) The speed range of the dump trucks used on the site varied from only 45 to 55 km/h. The low operating speed, the small range of speed and the elasticity of the tyres provided conditions that exacerbate the effects of dynamic loading. Up to 400 per cent additional pavement wear was estimated to take place at locations where the maximum dynamic loads were applied, when pavement wear was compared to that which would be expected from the application of the respective static loads.

(iv) A hypothetical traffic flow was considered comprising loading that was similar to that applied by the rear axle of the instrumented vehicle over a typical range of operating speed. The dynamic effects increased pavement wear by up to approximately 60 per cent at locations where the maximum dynamic loads were applied. When these loads were considered to travel at a uniform speed of 64 km/h the increase in calculated pavement wear rose to 100 per cent. The peak dynamic loads on the site occurred at 6 m intervals.

(v) On the basis of the work reported here, which was limited to a study of specialised vehicles, it is possible to identify the further work necessary to extend the results to wider use.

(a) although the study produced relationships between dynamic loading and road surface unevenness, these need to be confirmed over a
wider range of surface unevenness and vehicle type to ensure the wider applicability of the results; and

(b) the present work showed that there may be sections of road pavement where the dynamic axle-loads of heavy goods vehicles travelling at different speeds tend to concentrate with serious consequences for the life of the road pavement. There is a need to confirm the occurrence of these concentrations of load and to identify ways of minimising their effects.

8. REFERENCES


CEBON, D (1987) Assessment of the dynamic wheel forces generated by heavy road vehicles. Symposium on heavy vehicle suspension characteristics, Australian Road Research Board, Canberra, March.


9. ACKNOWLEDGEMENTS

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Plate 1: General view of test site

Plate 2: View of TRRL instrumented vehicle
Plate 3: View of dump truck in operation

Plate 4: High Speed Road Monitor surveying the site
Figure 1: Layout of Test Laboratory

Figure 2: Instrumented Pavement Section
Impulses from a set of 14 strain gauges

**Signal Conditioner**
- 14-channel carrier amplifier (x1000)
- Bridge balance and completion
- Energy to gauges
- Synchronisation of channels

**Filter**
- 4-pole Butterworth
- Removable > 250 Hz

**High-Speed Data Acquisition Unit**
- Analogue/digital converter
- High-speed clock
- Trigger

**HP Computer System Software**
- Data collection
- On-site graphics
- Software filtering
- Data analysis

*Figure 3: System developed for data collection*
Figure 4: Variation in profile from 1987 to 1989 for the nearside wheeltrack
Figure 5: Variation in profile from 1987 to 1989 for the offside wheeltrack
Figure 6: Change in rut depths for near and offside wheeltracks
Figure 7: Monthly rainfall and temperature records for 1987, 1988 and 1989 near the Welbeck site.
Figure 8: Weight of spoil transported along the haul road during 1987, 1988 and 1989
Figure 9: Relationship between roadbase strain per unit of dynamic load and vehicle speed

(i) GAUGE A22

\[ y = 42.005x^{-0.2256} \]

(ii) GAUGE A30

\[ y = -0.264x + 32.633 \]
Figure 10: Effect of speed on dynamic loading over a 40 m length of wheel-track for the rear wheels of a 16 tonne 2-axle rigid vehicle.
Figure 11: Effect of speed on dynamic loading over a 40 m length of wheel-track for the front wheels of a 16-tonne 2-axle rigid vehicle.
Figure 12: Effect of speed on dynamic loading over a 30 m length of wheel-track for the 30 tonne dump truck
Figure 13: Spectral analysis showing the dominant 3 Hz vertical oscillation present in dynamic loading for the instrumented vehicle.
Figure 14: Spectral analysis showing the dominant 3 Hz vertical oscillation present in dynamic loading for the dump truck at approximately 48.5 km/h
Figure 15: Dynamic load profiles: repeated runs of instrumented vehicle at approximately 47 km/h (rear nearside wheel)

Figure 16: Instrumented vehicle - comparison between mean dynamic and static wheel load for a range of speed
Figure 17: Relationships between peak load coefficient and speed for the test vehicles
Regression equation for model:
\[ y = (0.0281 - 0.0023R) + \left(0.0052 - 0.00501R\right)x_1^2 - (0.000253 + 0.000054R)x_1^2 \]

Figure 18: Instrumented vehicle - relationships between dynamic load coefficient \(y\), speed \(x_1\) and roughness \(R\)
Figure 19: Relationship between percentage increase in wear and speed for the test vehicles
Figure 20: Structural pavement wear - comparison between the effects of static and dynamic loading for the instrumented vehicle
Figure 21: Structural pavement wear - Instrumented vehicle at a constant speed of 64 km/h
Figure 22: Structural pavement wear—comparison between the effects of static and dynamic loading for the dump truck.
Figure 23: Structural pavement wear—comparison between the effects of static and dynamic loading for the dump truck
Figure 24: Structural pavement wear: comparison between the effects of static and dynamic loading for the dump truck.
Table 1: Total length of cracking (mm) per metre of wheeltrack

<table>
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<tr>
<th>Chainage (metres)</th>
<th>Offside</th>
<th>Nearside</th>
<th>Offside</th>
<th>Nearside</th>
<th>Offside</th>
<th>Nearside</th>
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<td>0</td>
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Table 2: Relationships between peak base strain per unit of dynamic load \((y)\) and speed \((x)\)

<table>
<thead>
<tr>
<th>Nearside gauge number</th>
<th>Regression equations</th>
<th>Offside gauge number</th>
<th>Regression equations</th>
</tr>
</thead>
<tbody>
<tr>
<td>A8</td>
<td>(y = -0.2196x + 26.88)</td>
<td>C1</td>
<td>(y = -0.4595x + 38.54)</td>
</tr>
<tr>
<td>A10</td>
<td>(y = -0.2065x + 26.75)</td>
<td>C2</td>
<td>(y = 36.10x^{-0.247})</td>
</tr>
<tr>
<td>A11</td>
<td>(y = 28.18x^{-0.356})</td>
<td>C5</td>
<td>(y = 45.74x^{-0.263})</td>
</tr>
<tr>
<td>A14</td>
<td>(y = 28.06x^{-0.239})</td>
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<td>(y = 35.69x^{-0.216})</td>
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<tr>
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<td>C13</td>
<td>(y = -0.325x + 27.29)</td>
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<tr>
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<td>(y = -0.361x + 33.20)</td>
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<td>(y = -0.3405x + 39.61)</td>
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<tr>
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<tr>
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<td>(y = 45.89x^{-0.245})</td>
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<tr>
<td>B28</td>
<td>(y = 35.03x^{-0.199})</td>
<td>C30</td>
<td>(y = 37.20x^{-0.187})</td>
</tr>
<tr>
<td>B27</td>
<td>(y = -30.9x^{-0.2185})</td>
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<td>(y = -0.135x + 19.6)</td>
</tr>
<tr>
<td>B26</td>
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<td>B29</td>
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