Influences of Vehicle Loading on Pavement Wear

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Executive Summary

1. Introduction

The design and management practices used for the highway network in both New Zealand and overseas are based on the static axle loads to which the road pavements are subjected. However as the loads are dynamic for each axle, varying as the suspension responds to the unevenness in the pavement surface, the actual loads applied to pavements are more complex. Furthermore the accumulation of these dynamic loads for the mix of vehicles in the fleet does not generate a uniform distribution of load along the pavement. Both these factors are believed to influence the level of pavement wear that is generated by heavy vehicles.

The investigation recorded in this report was carried out in 1996-1997. It uses the results of overseas studies to identify the sources of dynamic loading, to assess their effect on pavement wear, and to interpret these results in terms of New Zealand pavements and vehicles. The options for applying them to pavement management practices are evaluated.

2. Wheel Loads

The OECD adopted in 1992 the following terminology for wheel loads:

- stationary (constant) wheel loads,
- moving constant wheel loads, and
- moving dynamic wheel loads.

Stationary wheel loads are the static loads generated by a heavy vehicle and are the dominant factor in pavement wear. They are the basis of current pavement and vehicle design, and are those measured for legal load enforcement. They are influenced by tyre configuration (type, size, number, pressure), and axle configuration (single or groups).

Moving constant wheel loads are caused by various mechanisms that transfer portions of the stationary wheel loads between the wheels when the vehicle is in motion. Examples are: the longitudinal load transfers that occur during braking and acceleration, and the transverse transfers that occur during cornering, and the effects of road geometry (slope and crossfall).

Moving dynamic loads are generated by vibrations and oscillations of the vehicle and its elements. These cause loads to be applied to the road which range above and below their moving constant values.

The natural resonance modes of vibration of a vehicle can be split into two groups: low frequency modes corresponding to motions of the vehicle body (called sprung mass modes), and high frequency modes corresponding to motions of the axles and wheels (called unsprung mass modes).

The frequencies of these modes are determined by the stiffness of the suspension and tyres, while the magnitude of the response is controlled by the damping in the system and the magnitude of the excitation.

As the excitation is primarily generated by the road profile, the amplitudes are determined by road roughness and vehicle speed.

3. Pavement Types

The relative importance of these different loading sources depends on their impact on the pavement. Pavements may be rigid, with surfaces constructed of Portland Cement Concrete (PCC), or flexible. The latter normally consist of asphaltic concrete or chipseals as a surface layer, over unbound granular basecourse, and unbound granular sub-base layers, over the in situ material (subgrade).

The three main subgroups of flexible pavements are thin-surfaced (less than 40 mm thick), structural asphaltic concrete, and unsealed pavements (which are excluded from this investigation). Thin-surfaced pavements have either chipseal surfaces or thin (less than 40 mm thick) bituminous-mix surfaces that add no structural capacity to the pavement.

The model for describing the behaviour of thin-surfaced, unbound granular flexible pavements assumes that the thin surface layers do not contribute to the structural capacity of the pavement and that the stresses are dissipated through the depth of the granular cover layers above the subgrade. The main design criterion is to limit the vertical compressive strain in the subgrade to acceptable magnitudes because the theory presupposes that the primary mode of structural failure is permanent deformation in the subgrade.

However, the overseas literature on flexible pavements tends to concentrate on asphaltic concrete pavements, and on deformation, stresses and strains in the asphalt layer. This is not relevant to New Zealand roads which are mostly thin-surfaced flexible pavements using chipseal.

4. Wheel Load Effects

The ways in which stationary loads are applied to the pavement are influenced by the following factors.

Tyre construction

Opinions on the effects of bias ply tyres and radial ply tyres differ. However, the effects appear to be confined to the region near the surface of the pavement and are slight.

Tyre diameter and profile

These appear to have no significant impact except that, in general, smaller diameter and low profile tyres operate at higher tyre pressures for the same axle loads, and therefore cause increased surface stresses.

Single tyres and wide-base single tyres generate significantly greater pavement wear than dual tyres. Wide-base single tyres generate approximately twice the rutting depth of dual tyres carrying the same load. Ordinary single tyres are even more damaging.

Tyre inflation pressure

This affects the contact area of the tyre and the pressure distribution within that contact area applied to the pavement. In general the pressure is most uniformly distributed across the contact area when the tyre is inflated to the recommended inflation pressure for the load.

Higher inflation pressures lead to reduced contact areas and increased surface stresses. This influence is substantial at the surface and reduces with depth so that the impact on subgrade rutting is small.

Uneven inflation of tyres in a dual set can mean that the tyres behave almost like an ordinary single tyre. This has a major impact on the wear generated on the pavement.

Axle grouping
Axles in groups interact with each other to generate a combined strain response. The effect is relatively small and treating a group as generating the same wear as the equivalent number of single axles is not unreasonable.

Moving constant loads are generated by road geometry and by vehicle operations (acceleration and braking). They occur in a similar way for all heavy vehicles and will occur in predictable locations on the pavement. Fore and aft load transfers typically result in the load on some axles increasing by 5-10% while the load on others decrease. Transverse load transfers tend to be larger than longitudinal. For example those caused by geometry effects related to camber may increase loads by 19%, and those occurring during cornering can be much larger.

Many heavy vehicles have a static rollover threshold of only 0.3 g. This means that at this lateral acceleration the entire load has transferred from the inside wheels to the outside wheels. Lateral accelerations of this magnitude can be achieved at relatively modest speeds on highway curves.

Moving dynamic loads can result in the peak wheel loads being as high as double the static wheel loads. Factors influencing dynamic wheel loads are suspension performance, pavement profile, vehicle speed, and road roughness. Improved suspension performance can reduce dynamic wheel loads by as much as half.

5. Reducing Pavement Wear

Five mechanisms that can reduce the impact of these vehicle-generated influences on pavement wear are: load regulation, road pricing, pavement design, maintenance management, and education. The appropriateness of each of these mechanisms depends on which particular influence on road wear is being ameliorated as well as implementation, economic and political factors.

Load regulations
Regulations are already used to control some of the road damaging characteristics of heavy vehicles, e.g. axle load regulations. The regulation relating to allowable axle loads for tandem axles with different axle spacing however could be modified.

Road pricing
Road User Charges (RUCs) provide the basis for encouraging vehicle operators to optimise the pavement wear they generate by charging them explicitly for it. The wear component of RUCs is based on a fourth power relationship between axle loads and pavement wear. This relationship may have potential to be changed to some other power.

RUCs could be used to mitigate the influences of dynamic loading on pavement wear by encouraging use of "road-friendly" suspensions, as better suspensions can generate significantly lower dynamic loads under the same operating conditions.

Road pavement design practices
These practices could be modified to take greater account of the effects of loading, particularly of the moving constant loads which are, to a considerable degree, predictable from the geometry and layout of the road. Two options are: to modify the road geometry to minimise the load transfers and consequently the magnitude of the moving constant loads, or to adjust the pavement structure design to cope with the moving constant loads that will occur.

Maintenance management
Management of maintenance programmes can have a significant effect in ameliorating the effects of moving dynamic loads. As the level of dynamic loading is strongly influenced by road roughness, maintaining a lower level of roughness will reduce the level of dynamic loading and hence the associated pavement wear. The net effect is likely to be more frequent intervention at a lower level, with possibly a lower overall cost.

Education
Education could impact on reducing the pavement wear generated by these dynamic loads in two areas:

- Use of correct tyre inflation pressures: over-inflation of tyres or unequal inflation of tyres in a dual pair generates additional pavement wear which, while the magnitude is not great, the total sums are not insignificant.
- Inclusion of dynamic loading in design and management practices: an awareness by the pavement engineering community of the issues and factors will lead to improvements.

6. Conclusions

Vehicle loading factors that affect pavement wear are: static axle load; tyre configuration; tyre pressures; longitudinal load transfers due to gradient, acceleration and braking; transverse load transfers due to camber, crossfall and cornering; suspension load sharing; suspension dynamics.

Most overseas research on pavement wear cannot be directly applied to New Zealand pavements which generally are an unbound structure coated with a thin surface (that provides waterproofing and a running surface). Local research results relate to only specific aspects of pavement wear and response, and no models are sufficiently well developed to be able to replace the overseas data. Therefore these overseas data have to be used but the limitations of doing so must be kept in mind.

Static axle load
The single most dominant factor contributing to pavement wear is the static axle load. This is determined by the payload and the vehicle tare mass, and so opportunities are limited for reducing the magnitude of this factor. However, the current axle group load limits which allow higher axle loads for more widely spaced axles are not supported by the current knowledge of static load impacts. From the point of view of pavement wear, there is no reason why axles in a group should not have the same load limit as the same number of single axles. Allowing this would encourage more closely spaced axles which would reduce tyre wear and surface scuffing of the pavement, as well as improve vehicle handling.

Tyre configuration

Tyre configuration is already addressed in the present RUC structure. For example, comparing a type 27 vehicle (a two-axle trailer with single tyres) with a type 30 vehicle (the same trailer with dual tyres), the RUC for the type 27 is up to two times larger than type 30.

Tyre pressures

Tyre pressures, especially over-inflation and unequal inflation of dual tyres, can have a large effect on pavement wear. Education of road managers and operators is the best way to address this problem, because regulations would be difficult to enforce and incentives are not appropriate. Also it is in the operators' best interests to have correctly inflated tyres.

Load transfers

Load transfers, both longitudinal and transverse, that are related to road geometry and acceleration, cornering and braking are unavoidable. However, they should be factored into pavement design procedures. By reinforcing the most vulnerable parts of the pavement network, the performance of the system will improve.

Suspension dynamics and load sharing

Suspension dynamics performance could be improved through regulations and alterations to the RUC structure. For example, RUCs could be used to mitigate the influences of dynamic loading on pavement wear by encouraging use of "road-friendly" suspensions. An incentive in the form of a discount on RUCs could be used to encourage the adoption of these suspensions and would result in a reduction in the pavement wear generated by these vehicles. At the present time, techniques for assessing suspension road-friendliness have been developed but not yet implemented anywhere in the world.

Abstract

While pavement design and management practices are based on static axle loads, the actual loads applied to pavements are dynamic, varying as the suspension responds to the unevenness in the pavement surface. Furthermore the accumulation of these dynamic loads for the mix of vehicles in the fleet does not generate a uniform distribution of load along the pavement. Both these factors are believed to influence the level of pavement wear that is generated by heavy vehicles. Over the twenty years since the 1980s many studies have investigated the relationships between aspects of dynamic loading by vehicles and pavement wear.

This investigation, carried out in 1996-1997, reviews the sources of vehicle loading on pavements, assesses their effect on pavement wear, and interprets these results in terms of New Zealand pavements and vehicles. Having assessed the significance of the factors, the options for applying then to pavement management practices are evaluated.

1. Introduction

The models of pavement wear that underpin the design and management of the highway network in New Zealand and elsewhere are based on the static axle loads to which the pavement is subjected. The actual loads applied to pavements are however more complex. For each axle the loads are dynamic, varying as the suspension responds to the unevenness in the pavement surface. Furthermore the accumulation of these dynamic loads for the mix of vehicles in the fleet does not generate a uniform distribution of load along the pavement. Both these factors are believed to influence the level of pavement wear generated.

Over the past twenty years or so, many studies have investigated the relationships between aspects of dynamic loading by vehicles and pavement wear. Since 1992 two major overview reports have been published on this subject (OECD 1992; Cebon 1993), as well as a substantial parametric study using computer simulation (Gillespie et al. 1993) which includes an overview in its appendices. Cebon was involved in both the OECD and the Gillespie et al. studies, and therefore in some areas the three reports cannot be regarded as being independent of each other.

This present study carried out in 1996-1997 uses these three reports together with results from the other studies, where needed, to identify the sources of dynamic loading, to assess their effect on pavement wear and then to interpret these results in terms of New Zealand pavements and vehicles. Having assessed the significance of the factors, the options for reflecting them in pavement management practices are evaluated.

2. Wheel Loads

2.1 Introduction

A variety of interpretations appear in the literature on the meaning of "dynamic" wheel loads. To avoid confusion the OECD (1992) adopted the following terminology for wheel loads, which will be used in this study:

- stationary (constant) wheel loads
- moving constant wheel loads and
- moving dynamic wheel loads.

Stationary wheel loads are the static loads referred to in chapter 1 of this report. These are the basis of current pavement and vehicle design, and are those measured for legal load enforcement. Values for the stationary wheel (or axle) loads are normally obtained using weigh scales on a stationary vehicle on level ground.

Moving constant wheel loads differ from stationary (constant) wheel loads because of various mechanisms that transfer portions of the stationary wheel loads between the wheels when the vehicle is in motion. These transfers occur relatively slowly compared to the vertical dynamics of the vehicle and suspension. Examples of these load transfer mechanisms are: the longitudinal load transfers that occur during braking and acceleration, the lateral transfers that occur during cornering, and the effects of road geometry (slope and crossfall).

Moving dynamic loads are those generated by vibrations and oscillations of the vehicle and its elements. These cause loads to be applied to the road which vary above and below their moving constant values.

These three forms of wheel loads all act on the pavement vertically. Additionally, longitudinal wheel loads are generated by acceleration, braking and cornering. While it is clear that these loads have an impact on pavement wear, as is readily observed at intersections and corners, surprisingly little research has been done on either the magnitude of these forces or their contribution to road wear (OECD 1992; Gillespie et al. 1993). This study considers only the effects of vertical wheel loads.

2.2 Stationary Wheel Loads

Static or stationary wheel loads already form the basis of the current pavement design procedures and the road user charges (RUC) structure. However, the impact of static loads on pavement wear depends on tyre configuration, tyre pressure and axle configuration.

2.2.1 Tyre Configuration

Three basic tyre configurations are in common use in heavy vehicles. These are dual or twin tyres, wide-base single tyres and single tyres. The conversion of axle loads to Equivalent Standard Axles (ESA) for pavement design and management applications incorporates an allowance for the differences in road wear generated by these different tyre configurations, as follows.

- Dual tyres, an 8.2 tonne axle load is deemed to generate one ESA;
- Wide-base single tyres, an axle load of 7.3 tonnes generates one ESA;
- Ordinary single tyres, an axle load of 6.7 tonnes generates one ESA.

The implication is that these loads generate equivalent levels of pavement wear.

In addition to these three basic configurations, there are variations in tyre construction, rim size and tyre profile. Two generic types of tyre construction are used; bias ply and radial ply. The most widely used wheel rim size is 22.5 inches (57.15 cm) diameter. However, in recent times the trend has been towards using smaller diameter rims for vehicles carrying high volume loads. Traditionally tyres have a depth (of the sidewall) approximately equal to the tyre width. Low profile tyres have a depth that is typically between 65% and 80% of the tread width. Generally, wide-base single tyres and smaller diameter tyres have this low profile aspect ratio, although low profile standard size tyres in both dual and single configuration are not uncommon. None of these variations are currently taken into account in estimating the load equivalency values for axles.

Bias ply tyre construction results in a stiffer sidewall, which has a small effect on the vehicle's suspension dynamics. Gillespie et al. (1993) state that the contact patch area of a bias ply tyre is basically the same as that of a similarly loaded radial tyre. However, both Marshek et al. (1985) and Yap (1988) show from measurements that the contact patch for a bias ply tyre is about 10-15% larger than that for a similar radial ply tyre.

Yap (1988) also shows the contact pressure distributions for bias ply and radial ply tyres and their sensitivity to changes in load and inflation pressure. The two types of tyre behave quite differently and it is difficult to summarise the differences with simple trends. In general, a bias ply tyre produces maximum contact pressure values which are 25% - 50% lower than those of a similarly configured radial tyre. However, the pressure distribution for a bias ply tyre is more sensitive to loads, and at high wheel loads this difference disappears.

Two other effects related to tyre construction impact on pavement wear. The first is referred to by Gillespie et al. (1993) as "squirm". As the tyre rolls it deforms to into a flat shape requiring the tread to squirm into the contact patch. The levels of shear stress at the interface generated by this squirming are higher for bias ply tyres. This is reflected in the higher levels of tyre wear observed for bias ply tyres. As pavement performance models do not include shear stresses, it is difficult to quantify the pavement wear associated with shear loading.

The second effect arises from the differences in the camber thrust characteristics of the tyre (Gillespie et al. 1993). Bias ply tyres tend to climb out of ruts while radial ply tyres will track in them thereby decreasing the lateral wander of vehicles in their lanes. It appears that bias ply tyres apply lower contact pressures to the pavement and accordingly will generate less pavement wear. However this effect is relatively small. Radial ply tyres have many operational advantages in terms of vehicle handling, stability and tyre life, and are gradually replacing bias ply tyres.

The main impact of these configurations and variations of tyres on pavement wear comes about through changes in the tyre contact-patch size and shape, and the pressure distributions across that patch. This determines the contact stresses applied to the pavement and affects the strains in the pavement layers. Dual tyre configurations result in two adjacent contact patches that interact with each other. Small diameter and wide-base single tyres generally operate at higher inflation pressures and have smaller contact patch areas.

Various recent studies (Christison et al. 1978; Huhtala et al. 1992; Bonaquist et al. 1988) have looked at the impact of tyre configuration on pavement wear. These studies have generally measured pavement strains or deflections and then used a power law (typically fourth power) to determine the impact on pavement damage.

The appropriateness of using fourth power depends on the type of pavement damage (rutting or cracking) and is influenced by pavement characteristics. The implications for New Zealand pavements are discussed in chapter 3 of this report.

The OECD (1992), in summarising these studies, reports that wide-base single tyres generated strains between 50% and 100% greater than dual tyres carrying the same load. Both Gillespie et al. (1993) and Cebon (1993) concur with this finding. However, Gillespie et al. (1993) in reporting their own modelling studies found asphalt bending strain values between 7% and 30% greater for wide-base single tyres, between 55% and 74% greater for ordinary single tyres, and between 7% and 25% greater for small diameter low profile dual tyres. The range of strains relates to variations in the asphalt thickness. This modelling by Gillespie included the changes in contact patch area but did not include any change in contact pressure distribution. Wide-base single tyres behaved somewhat differently from ordinary single tyres and low profile dual tyres with respect to pavement thickness. Both ordinary single tyres and low profile dual tyres generated higher strains for thinner pavements that decreased as the pavement thickness increased. Somewhat surprisingly with the wide-base single tyres, the strain levels increased with increasing pavement thickness. It should be emphasised that these strains are bending strains in the asphalt and reflect the fatigue damage to the asphalt layer. The lower strain values in the asphalt layer associated with thinner pavements were offset by higher strains in the basecourse and subgrade, and consequently caused greater damage in these layers.

2.2.2 Tyre Pressure

Most flexible pavement analysis has assumed that the tyre contact patch is circular and that the pressure distribution is uniform and equal to the tyre inflation pressure. However, experimental studies (de Beer 1994; Marshek et al. 1985; Yap 1988) have shown a more complex pressure distribution with pressure peaks as high as double the inflation pressure. Figures 2.1 and 2.2 show an example of these contact pressures taken from Yap (1988). This contact pressure distribution is of great significance in considering pavement wear, as it is the stress applied to the pavement surface.

From Figure 2.1 there appears to be very little influence from tread band bending on the longitudinal pressure distribution. Figure 2.2 shows the influence of inflation pressure on the transverse pressure distribution for a radial tyre. At lower inflation pressures the sidewall stiffness increases the contact pressure near the edges of the contact patch. As the inflation pressure is increased, the contact pressure at the centre of the tyre increases and the point of maximum contact pressure moves from the edge of the contact patch to the middle. For bias ply tyres, the impact of the sidewall stiffness is more significant and the effect of increased inflation pressure is less.

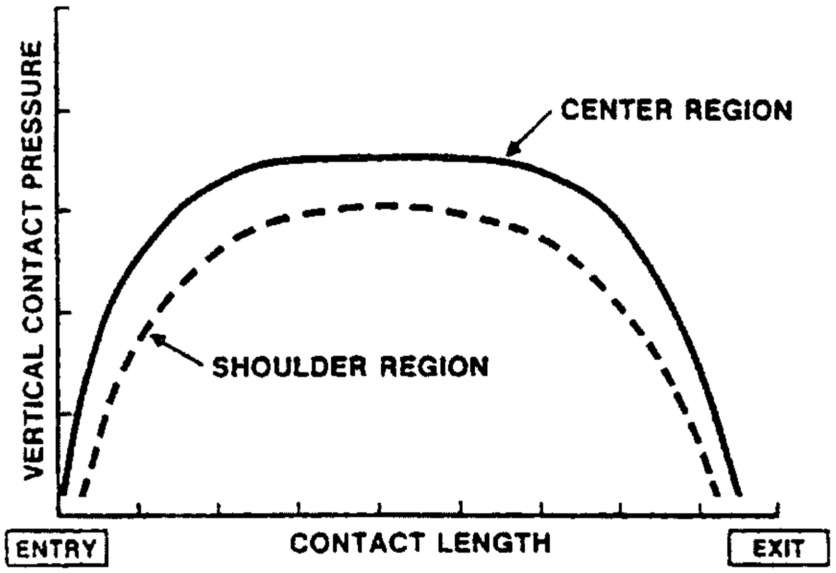


Figure 2.1 Longitudinal contact pressure distribution (from Yap 1988).

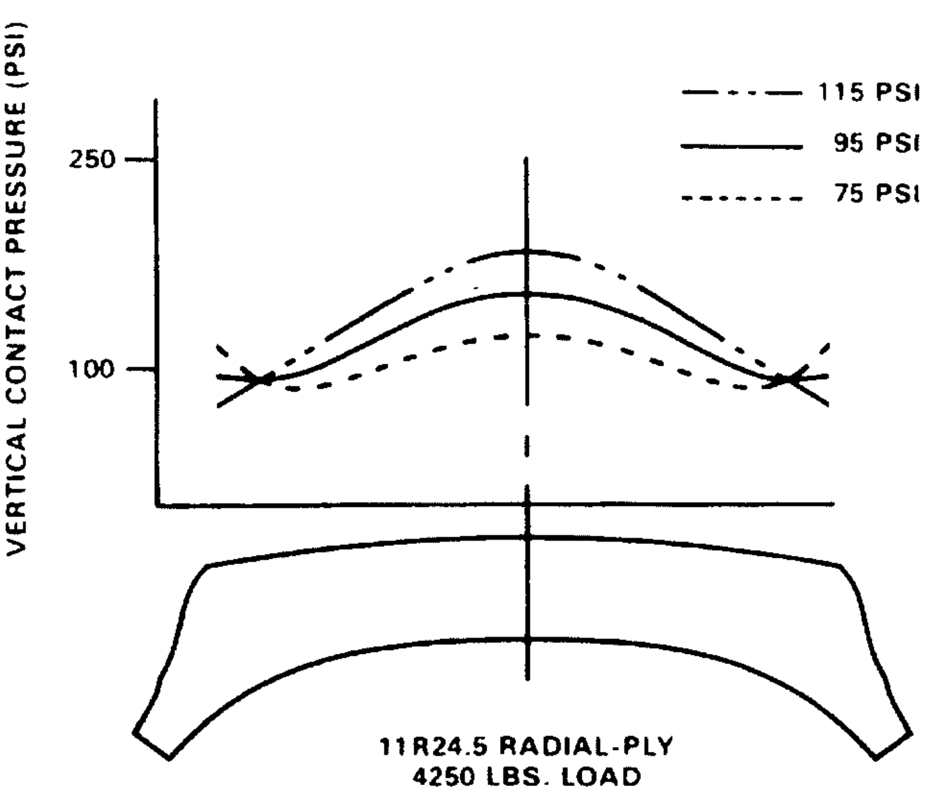


Figure 2.2 Transverse contact pressure distribution across the pavement surface (from Yap 1988).

For an appropriately inflated tyre, the contact pressure distribution is relatively uniform and the contact patch is approximately rectangular in shape. As the inflation pressure increases, the contact patch becomes more elliptical in shape and the difference between the peak contact pressure and the mean contact pressure increases. At lower than optimal inflation pressures the sides of the contact patch become concave and the peak contact pressures occur at the edges of the contact patch.

With dual tyre configurations a further issue of unequal tyre pressures arises. Most of the studies comparing wide-base single tyres with dual tyres ensured that both tyres in the dual set were identical and correctly inflated to give equal contact pressures. In practice it is common that this is not so. Huhtala et al. (1988) suggested a number of factors, e.g. uneven inflation pressure, uneven tyre wear, axle bending, and road unevenness, all of which could generate unequal contact pressures for the two tyres of a dual set. They conducted a test with unevenly inflated dual tyres (one at 500 kPa and one at 1000 kPa) to simulate this situation and found that this significantly reduced the differences in pavement strain generated by dual tyres and wide-base single tyres.

2.2.3 Axle Configuration

When the spacing of adjacent axles is not large, their effect on the pavement is not independent of each other. Typically a location on a pavement will show some response to an approaching axle when the axle is two metres or so away, and therefore if two axles are spaced less than two metres apart they will have a combined effect on the pavement. The precise spacing at which the axles cease to act independently is a function of the pavement structure. Where axles act together in this way they are known as axle groups. Groups of two axles (tandem) and three axles (tridem) are in common use in New Zealand. Under New Zealand heavy vehicle regulations a vehicle can have at most two axle groups. Thus if a vehicle has three axles they are regarded as one single axle and one tandem group regardless of spacing (except on a semitrailer where they are one tridem group).

OECD (1992), Cebon (1993) and Gillespie et al. (1993) have almost identical comments on this issue, which may reflect Cebon's influence in all three reports, but actually they come to opposing conclusions. Cebon and Gillespie's appendices both state that tandem and tridem axle groups can carry more weight than the equivalent number of single axles for the same level of road damage. The OECD report in almost the same words says that tandems and tridems can carry less weight than the equivalent number of single axles.

The reason that axle groups are believed to be able to carry higher loads than the same number of single axles is based on the longitudinal bending strain response in the asphalt layer. As an axle passes, the bottom surface of the asphalt undergoes compression, then tension, and then compression again. If a subsequent axle follows closely enough behind, the associated initial compressive strain will reduce the tensile strain from the first axle, thereby reducing the magnitude of the stress cycles the pavement is subjected to. However, because so few New Zealand pavements have a structural asphalt layer this argument has limited relevance in this investigation.

All the three reports suggest that the optimal spacing is approximately 1.2 m. However, all three reports also go on to state that this fact is reflected in the axle spacing load / geometry regulations of a number of countries, and refer to Schacke & Barenholdt (1986). However, this reference quotes an EC (Council of the European Communities) directive for axle load limits, which, like the New Zealand regulations, allow lower axle limits for groups than for the same number of single axles and, more critically, allow greater loads for wider spacing. This contradicts the original assertion. In New Zealand, however, the road user charges are lower for axle groups than for the same number of single axles (compare the two axle trailer - type 30 with the tandem axle semitrailer - type 29).

The modelling analysis conducted by Gillespie et al. (1993) showed that, for flexible pavement fatigue damage, the influence of axle spacing was very small especially for thin pavements. Thus axle groups could be treated as a series of single axles. This effectively contradicts the literature survey findings in the same report. The reason for this lack of interaction between the axles in a group was that, for the range of pavement thickness considered, there was only a very small influence on asphalt bending strain from the adjacent axle for realistic axle spacing values.

In terms of the New Zealand context, the main source of pavement damage is permanent deformation in the lower layers rather than asphalt fatigue or cracking damage. Axle spacing does affect this because axles generate a vertical compressive strain response in these layers at horizontal distances greater than the typical axle spacing. So the response to an axle group is not identical to the response to the same number of single axles.

This discussion has been limited to the effect of axle configuration on static loading. Axle groups normally have load-sharing mechanisms and dynamic characteristics that influence both moving constant loads and dynamic loads. These factors are discussed in the following sections 2.3 and 2.4 of this chapter.

2.3 Moving Constant Wheel Loads

Moving constant wheel loads are generated by mechanisms that transfer portions of the stationary wheel loads between the wheels. The transfers can occur in two basic directions: longitudinal or along the vehicle, and transverse or across the vehicle. They are very slow relative to the frequencies involved in the vertical dynamics of the vehicle.

2.3.1 Longitudinal Load Transfers

A number of factors cause a longitudinal redistribution of the axle loads. These include topography, vehicle acceleration and deceleration, aerodynamics, and the influence of suspension systems and vehicle geometry.

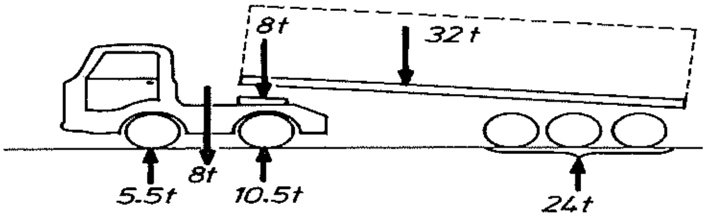
Road geometry generates some of these transfers. On a longitudinal slope load will shift from the uphill axles to the downhill axles. These effects can be quite large, and the OECD (1992) report gives an example of a two axle truck on a 10% slope resulting in a 6% increase in load on the rear axle and a 10% reduction on the front axle.

Loads also transfer longitudinally between axles as a result of torque applied to the wheels from drive or braking, and aerodynamic forces applied to the vehicle body. Figure 2.3 shows an example of these load transfers under acceleration and drive. The OECD (1992) and Gillespie et al. (1993) give similar values for the magnitude of these effects. At full power acceleration from low speeds, the OECD (1992) indicate up to a 17% increase in the drive axle load while Gillespie et al. (1993) suggest an increase of around 10%. These calculations are based on different vehicle configurations, with the OECD considering a tractor-semitrailer and Gillespie using a straight truck. At highway speeds the load transfers due to drive torque are given as 2% (OECD 1992) and 3% (Gillespie et al. 1993).

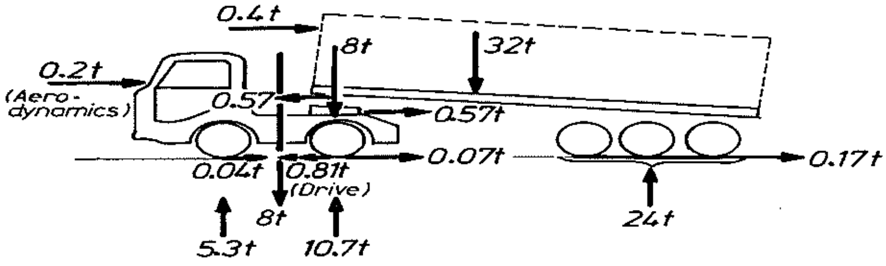
Vehicles when braking can achieve a much greater magnitude of acceleration than when driving. However, good driving practice avoids the use of these high braking levels except in emergency situations. Experimental studies have shown that most braking occurs at less than 0.1 g deceleration. At this level, straight trucks experience a load transfer onto the front axle of about 5% of the weight of the truck (Gillespie et al. 1993). For combination vehicles the change is less.

The discussion to this point has been about load transfers from one end of the vehicle to the other. In New Zealand, heavy vehicles usually have at least one axle group, and suspensions on axle groups are generally required to have mechanisms that share the load approximately equally between the axles in the group. These mechanisms must counter a number of factors that generate load transfers between the axles, including braking and driving torque, road geometry and vehicle inclination. From a pavement wear perspective, it is desirable that this load sharing be as effective as possible. However, from a vehicle operations viewpoint, this is not always so. For example, the suspension of a 3-axle tractor with a single drive axle (known as a 6x2) will normally be designed to transfer additional load from the non-driven axle to the driven axle when engine power is applied to increase the adhesion and traction. In most instances, equal load sharing also benefits the vehicle because it improves braking and handling.

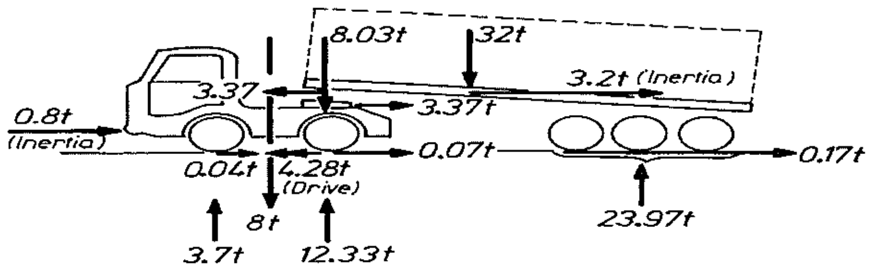
In spite of this, some load equalisation devices are ineffective. The OECD (1992) reports that, for some suspensions, raising one axle relative to the other(s) can result in axle load increases of as much as 0.2 tonnes per mm lift. This implies that, on undulating roads, peaks and troughs occur in the applied wheel loads that are related to this quasi-static process. These effects are a function of suspension design, and better suspensions show almost no load variation.



(a) At Rest



(b) At Steady Speed



(c) Accelerating at 0.1g (1ms^{-2})

Figure 2.3. The longitudinal load transfers that occur in a heavy vehicle, (a) at rest, (b) at steady speed, and (c) accelerating at 0.1 g (1ms^{-2}).

This lack of load sharing performance can also interact with other vehicle design factors. Variations in the fifth wheel height* on tractor units mean that a semitrailer, which is used with different tractors, will not always operate at the same inclination. If this semitrailer does not have an effective load-sharing mechanism on its rear bogey, the mean axle loads will not always be equal leading to unnecessary additional pavement wear.

2.3.2 Transverse Load Transfers

Road geometry and vehicle manoeuvring generate transverse load transfers across the axles. The road geometry influences come from crossfall and/or camber in the road surface. These factors can be significant, as shown by the OECD (1992) which reports a 19% increase in wheel loads on the downhill side for a 3% cross-slope. This is, of course, matched by an equivalent reduction in wheel loads on the uphill side. As all vehicles are affected by the road geometry in substantially the same way, this will cause excessive pavement wear on the downhill side of this pavement.

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* The fifth wheel is the coupling device on a tractor unit for connecting semitrailers. The height of the fifth wheel controls the attitude of the semitrailer.

Similarly, as a vehicle travels around a curve the load is transferred from the wheels from the inside of the curve to those on the outside of the curve. This effect depends primarily on the geometry of the vehicle and its load, although the suspension roll stiffness has an influence. The magnitude of this transfer can be large. Heavy vehicles can have a rollover threshold as low as 0.3 g, or even less. This is the level of lateral acceleration at which the vehicle will roll over, and it can be achieved at relatively modest speeds around roundabouts or highway curves. At speeds just below the critical value, the outer wheels are carrying double their stationary constant loads and thus the inner wheels are carrying nothing.

2.3.3 Load Sharing Coefficient

The previous two sections (2.3.1 and 2.3.2) describe the mechanisms by which these moving constant load transfers occur and the scale of each. However, they do not provide any information on the overall magnitude of these loading effects. During the various studies to measure dynamic wheel force conducted in the 1980s, load sharing was measured and this provides an indication of this overall magnitude.

A measure known as the "Load Sharing Coefficient" (LSC) was introduced by Sweatman (1983). It is defined as:

$$\text{LSC} = \frac{\text{Mean measured wheel load on a wheel}}{\text{(Total group static load / Number of wheels in group)}}$$

This measure quantifies the accumulation of some but not all of the two transfer types discussed in the previous two sections. For longitudinal transfers, it does not account for road undulation-induced transfers because these would be expected to average out to zero. Some braking- and drive-induced transfers would cancel each other but as the mechanisms are not symmetric the sum need not be zero. Transfers related to vehicle geometry factors are accounted for. For transverse load transfers, this measure does reflect road geometry-induced transfers, but transfers due to cornering forces will cancel to some extent though again not necessarily totally.

Sweatman's wheel force measurements were all done on the offside leading axle for tandem groups and the offside middle axle for tridems. These resulted in LSC values that were almost all less than unity. The exception was a torsion bar suspension with a value of 1.05. The range of values for LSC reported is 0.791 to 1.05. Sweatman attributes 2% to 4% of this load transfer to camber/cross-slope effects, and the rest to effectiveness of the load-sharing mechanisms. As these tests were undertaken on straight roads at constant speed, the effects of cornering and braking are not present.

An interesting aspect of these results is that the worst performing suspension was a walking beam type, which is specifically designed for good static load sharing. Mitchell (1987) also conducted a series of low speed axle weight measurements to look at load sharing. Quantitatively his results are similar to Sweatman's but the relative ranking of different suspension types differs slightly. Woodrooffe et al. (1986) investigated the effect of fifth wheel height on quasi-static load sharing for a tractor semitrailer configuration. His ranking of suspensions differs from both Sweatman and Mitchell in that the walking beam type performed best.

2.4 Moving Dynamic Wheel Loads

These are generated by oscillations of the vehicle and its elements in response to excitations generated primarily by the vertical displacement inputs to the wheels from the road surface. The vehicle response to these inputs can be separated into two broad categories:

- the low frequency modes, which are characterised by motions of the whole vehicle body and are called the sprung mass modes, and
- the higher frequency modes, which are characterised by motions of the axles and wheels and are called unsprung mass modes.

Some of these resonance modes are illustrated in Figure 2.4.

2.4.1 Sprung Mass Modes

These are motions in which the body above each axle is moving in phase with the axle, and the total flexibility between the road and the body is the sum of the flexibilities of the tyres and suspension. For a rigid body, the three fundamental modes of motion are roll, bounce, and pitch.

- Roll, which is a rotation about a longitudinal vehicle axis, is not normally significant except on rough roads.

Thus the two modes of interest are bounce and pitch:

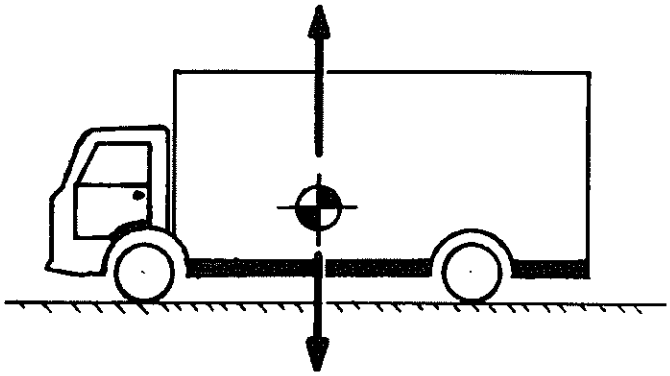
- Bounce occurs when both ends of the vehicle are moving in phase, while
- Pitch occurs when they are anti-phase.

In practice the two modes are normally hybrids of these two motions. The frequencies of these motions are usually between 1.5 Hz and 4 Hz. These vertical movements of the whole vehicle mass are reacted against the pavement and are a primary source of dynamic wheel forces.

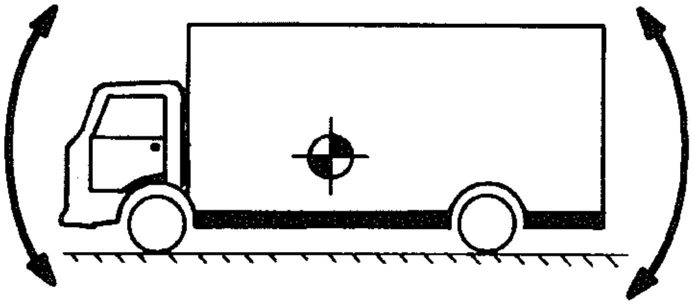
The frequency, damping and amplitude of these modes are strongly influenced by the suspension design. In general, softer suspensions lower the frequencies of the resonance modes. These then generate lower accelerations and hence lower wheel forces. Higher damping attenuates the motions and also reduces the wheel forces. For some suspensions the stiffness is dependent on the amplitude of the motion and this can have a significant impact. For example, steel leaf-spring suspensions have interleaf friction forces that provide some damping. These forces are initially very high which means that, for small motions, the spring is effectively locked and the only "springs" in the system are the tyres. These are relatively stiff and very lightly damped, and thus result in relatively high wheel forces.

2.4.2 Unsprung Mass Modes

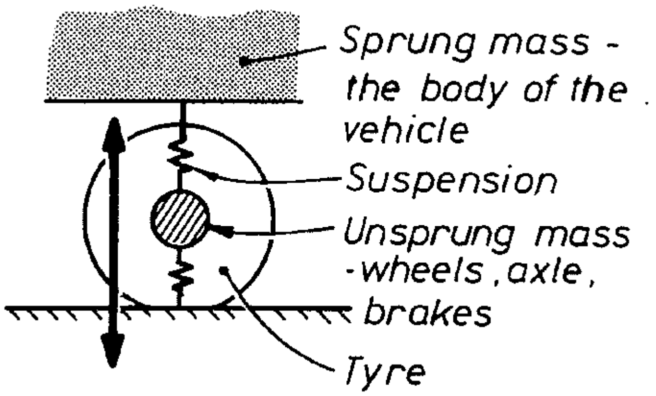
At higher frequencies (usually between 10 and 15 Hz) the axles oscillate vertically, relative to the vehicle body. As the axles are not supported by the springs they are considered unsprung and these modes are called unsprung modes. Where an axle group is involved, the axles are normally connected to each other through some form of load-sharing mechanism. Through this mechanism they can interact with each other to produce more complex motions.



(a) Vertical Translation, "Heave"



(b) Pitch



(c) "Wheel hop" - Vertical translation of the unsprung mass

Figure 2.4 Vehicle resonance modes for (a) heave, (b) pitch, and (c) wheel hop.

For example, with a traditional walking beam suspension the axles are connected to each other by two rigid beams, which are centrally pivoted to allow load transfer from one axle to the other. To be effective the central pivots must be free to rotate and typically are not damped. The result of this is that anti-phase oscillation of the two axles is very lightly damped and, once excited, will continue through numbers of cycles, thus generating high dynamic loads.

By reducing the spring stiffness, softer suspensions with lower sprung mass resonance frequencies result. These tend to isolate the sprung mass from the excitations generated by the road profile, with the result that most of the input motion is absorbed by movement of the unsprung mass rather than the sprung mass. This produces improved ride and, because the masses being accelerated are the smaller unsprung masses (the axles and wheels) rather than the larger sprung mass (vehicle body), the resulting wheel forces are lower.

2.4.3 Magnitude of Dynamic Wheel Loads

Many studies (Hahn 1985; Mitchell & Gyenes 1989; Sweatman 1983; Woodrooffe et al. 1986) have been undertaken to measure dynamic wheel loads under a range of test conditions. The most widely used measure for quantifying dynamic wheel loads is the dynamic load coefficient (DLC) which is defined as follows:

$$\text{DLC} = \frac{\text{Standard deviation of wheel load}}{\text{Static wheel load}}$$

Some authors use "mean wheel load" rather than "static wheel load" for the denominator, but usually the difference between these is small. Sweatman (1983) demonstrated that the distribution of dynamic wheel forces is approximately normal and hence DLC provides a complete characterisation of the magnitude of the dynamic components as a proportion of the static load.

Dynamic wheel force magnitudes (and hence DLC values) depend not only on the suspension type but also on the vehicle speed and pavement roughness. The DLC values measured in the studies mentioned above range from 0.02 for a vehicle with a soft well-damped suspension operating at relatively low speed on a smooth road, to 0.4 for a vehicle with stiff under-damped suspension operating at higher speed on a rough road. Under similar operating conditions of highway speed on a road of moderate roughness, Sweatman (1983) recorded DLC values ranging from 0.13 to 0.27 depending on suspension type.

As stated above, the distribution of dynamic wheel forces has been shown to be approximately normal. This means that for 68% of the time the wheel loads are within ±1 standard deviation of the static load, for 95% of the time they are within ±2 standard deviations, and for 99% of the time they are within ±3 standard deviations. As the DLC is the normalised standard deviation, this can be used to quantify the dynamic wheel forces in more detail.

For example, the peak dynamic wheel forces will be approximately 3 DLCs above the mean, so if a measured DLC value is 0.2, the corresponding peak dynamic wheel forces are 1.6 times the static wheel forces. For a particular DLC value, it is possible to generate a statistical distribution of wheel forces along the pavement.

Eisenmann (1975) used this distribution to calculate an expected level of pavement wear associated with dynamic loading using the fourth power relationship. However, he assumed that the distribution of wheel forces along the pavement is random. This implies that the mean wheel force applied at any point on the pavement is the same as that applied at any other point when averaged across the vehicle fleet. Recent research (O'Connor et al. 1996) however has shown that this is not the case and that there is a pattern of spatial repeatability in the wheel force distributions when averaged across a large number of vehicles. The peaks and troughs in these long-run average wheel force distributions were ±10% from the overall mean.

2.4.4 Pavement Factors Affecting Dynamic Wheel Loads

Pavement unevenness is the primary source of the excitations that stimulate the vehicle oscillations generating dynamic wheel loads. Generally a pavement profile contains components at wavelengths ranging from fractions of a millimetre to kilometres. However, wavelengths shorter than about 0.25 m will be enveloped by the tyre and have no influence on the vehicle vertical dynamics. Similarly wavelengths greater than about 50 m will have no impact on vertical dynamics. If the vehicle is travelling at 100 km/h, the 50 m wavelength corresponds to an excitation at 0.5 Hz, with lower speeds corresponding to lower frequencies still.

Figure 2.5 shows the power spectral density (PSD) function of a typical pavement profile plotted on a log-log scale. The amplitude of the PSD increases with increasing wavelength (i.e. decreasing wavenumber). The temporal frequency (Hz) of the excitation applied to the vehicle is related to the spatial frequency (wavenumber) of the profile by the vehicle speed. As the vehicle speed increases, a particular temporal frequency will correspond to a lower spatial frequency value and consequently to a greater excitation amplitude. Thus as the vehicle speed increases, the apparent amplitude of the excitations increase and the road appears rougher.

All the frequency components of the profile provide excitation to the vehicle but the vehicle response is much larger at frequencies near its sprung and unsprung resonance modes, and these components dominate the resulting wheel forces. The specific pavement profile wavelengths that excite the vehicle resonance modes depend on the vehicle speed. Generally short abrupt features such as potholes, poorly filled trenches and bridge abutments consist of a group of short wavelength components that lead to the unsprung mass modes being excited. Longer wavelength components, such as those caused by ground settlement, result in the sprung mass modes being excited.

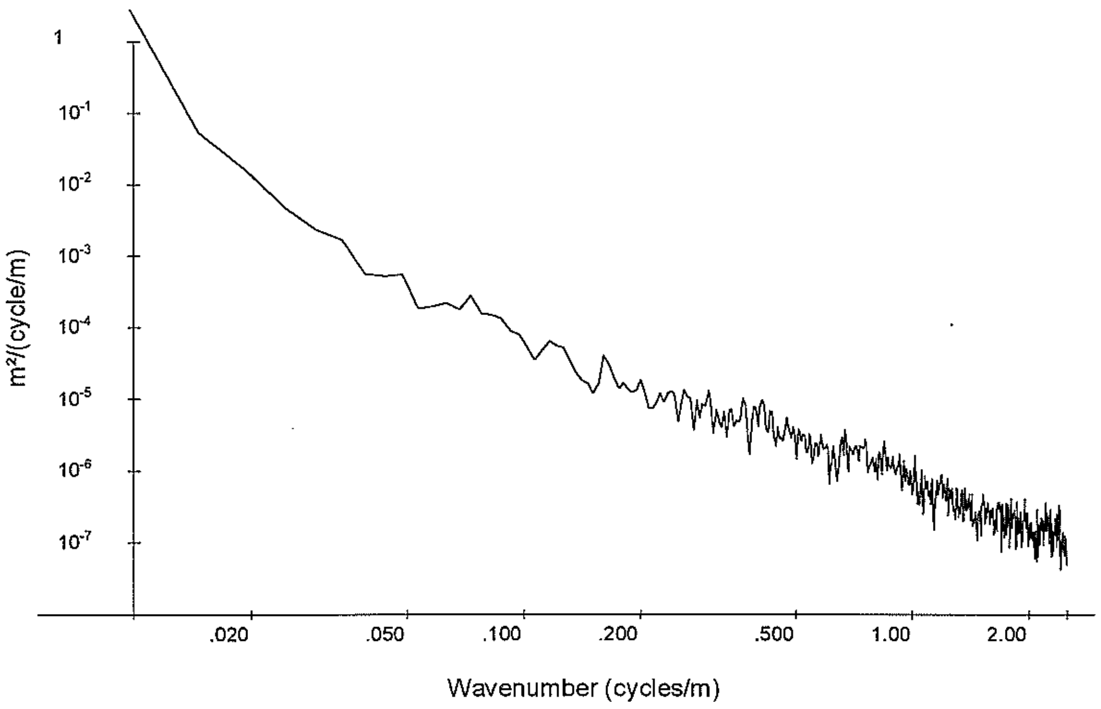


Figure 2.5 Power Spectral Density for a typical pavement profile.

Rougher roads generate greater dynamic loads given the same vehicle speed. Sweatman (1983) found that DLC increased in proportion to the square root of road roughness. Gillespie et al. (1993) and de Pont (1994) both found a linear relationship. The International Roughness Index (IRI), which is commonly used to quantify road roughness, is linearly proportional to the amplitude of the pavement profile. If the vehicle suspension was a linear dynamic system, its response would be proportional to the amplitude of the excitation and thus to the roughness. Although vehicle suspensions are not necessarily linear in response, this does provide some theoretical justification for a linear relationship.

2.4.5 Vehicle Factors Affecting Dynamic Wheel Loads

A number of the vehicle factors affecting dynamic wheel loads have already been discussed in previous sections of this chapter. Suspension and tyre stiffness values affect the natural frequency of the resonance modes of the vehicle. In fact, changing the suspension stiffness impacts primarily on the natural frequency of the sprung mass modes while altering the tyre stiffness impacts primarily on the unsprung mass modes of resonance.

The underlying relationship is that the natural frequency is proportional to the square root of the stiffness. This relationship is not exact because the two types of resonance mode interact with each other and both frequencies change, but it has the correct order of magnitude.

For example, using a quarter car model with typical stiffness values for a heavy vehicle with air suspension, if the suspension spring stiffness is reduced by a factor of two the sprung mass resonance frequency is reduced by 35% (the square root relationship predicts 41%), and the unsprung mass resonance frequency by 5%. Similarly reducing the tyre stiffness by a factor of two reduces the frequency of the sprung mass resonance by 8%, and that of the unsprung mass resonance by 30%.

A second vehicle factor affecting the natural frequencies of the resonance modes is mass. Increasing the vehicle mass reduces the natural frequency. As with stiffness, changing the sprung mass primarily affects the frequency of the sprung mass resonance modes and changing the unsprung mass primarily affects the frequency of the unsprung mass resonance modes. The underlying relationship is similar to the stiffness one with the natural frequency being inversely proportional to the square root of the mass. Thus increasing the mass or lowering the suspension stiffness or both can lower the natural frequency of the sprung mass modes. In normal vehicle operations, a heavy vehicle operates under a range of loading conditions and hence masses, which presents difficulties for designers in matching the suspension stiffness to the load. One of the great benefits of air suspension is that the air pressure and consequently the spring stiffness is adjusted to compensate for the load. Thus the stiffness and mass are matched across a wide range of loading conditions.

The issue of mass is a little more complicated than just outlined. If the sprung mass resonance modes were purely body bounce, then the sprung mass of the vehicle would be the key factor. However, the sprung mass modes also include a pitch motion and this is influenced by the rotational inertia of the sprung mass about a transverse horizontal axis through the centre of gravity. This inertia depends on both the mass and the distribution of that mass. As a general principle, concentrating the mass at the centre of gravity produces a low inertia value and a higher natural frequency for the pitch resonance, while concentrating the mass at the extremities of the vehicle increases the inertia and lowers the frequency. As with mass, the underlying relationship involves a square root.

Provided the damping is adequate, lowering the natural frequency of the sprung mass resonance modes reduces the dynamic wheel loads. This is because the forces generated are determined by the accelerations of the masses, not by the displacements. For a particular amplitude of oscillation, the acceleration is proportional to the square of the frequency. Thus, although at lower natural frequencies the excitation amplitude from the pavement increases, this effect is much less than the reduction in acceleration.

Dynamic wheel loads also tend to increase with vehicle speed. The primary mechanism for this was described in the previous section 2.4.4 on pavement factors. Sweatman (1983) reports a linear relationship based on curve fitting to measured data. Gillespie et al. (1993) suggest a more complex relationship based on the vehicle modelling results used in their study.

The main reason for this additional complexity is a phenomenon known as "wheelbase filtering". Any pavement irregularity excites first the leading axle and then the trailing axles. The vehicle's axle spacing and speed determine the interval between these inputs. If this interval coincides with the period of the bounce mode of vibration, this motion will be reinforced and the associated dynamic wheel forces will increase. At other intervals the motion will not be reinforced and when the interval is half the period the motion will be attenuated.

For the pitch mode of resonance, maximum reinforcement occurs when the interval is half the period and maximum attenuation when the interval equals the period. The interactions between axles in a group are also affected by this phenomenon. For example, a vehicle with a 5 m-axle spacing travelling at 25 m/s will receive bounce mode reinforcement at 5 Hz and pitch mode reinforcement at 2.5 Hz. Depending on suspension type the natural frequencies of these resonance modes are likely to be in the range 1.5 – 4 Hz.

This implies that the bounce mode reinforcement will occur in a speed range of 7.5 – 20 m/s and the pitch mode reinforcement at some speed in the range 15 – 40 m/s. Walking beam suspensions undergo an anti-phase axle hop oscillation, which is equivalent to pitch. With an axle spacing of 1.5 m and a resonance frequency of 8 Hz, this will be reinforced at a speed of 24 m/s, which is well within normal vehicle operating conditions.

3. Implications for Pavement Wear

3.1 Introduction

The two broad categories of pavements are rigid and flexible. They are distinguished primarily by the type of material employed in their construction. However, the material used also affects the manner in which loads are carried.

The surface of a rigid pavement is a Portland Cement Concrete (PCC) slab, and the load is carried in bending. The method of design and analysis normally used is slab or plate theory. Usually, because of the load-carrying capacity of the slab, the PCC layer is placed directly over a sub-base. A PCC slab is much stiffer than the underlying materials; thus the slab distributes the load applied by the vehicles over a larger area, spanning localised weak spots. The critical stress is the tension in the slab, created by temperature changes, shrinkage, and vehicle loading, and it must not exceed the capacity of the material.

Flexible pavements basically cover all other types of pavements, and normally consist of asphaltic concrete or chipseals as a surface layer, unbound granular basecourse and unbound granular sub-base layers, over the in situ material (subgrade). Flexible pavements carry the load in shear and compression, and spread the load with depth. The method of analysis is usually by linear elastic or visco-elastic layered theories. Three main subgroups are thin-surfaced (less than 40 mm thick), structural asphaltic concrete layers, and unsealed pavements (which are excluded from this discussion).

A structural asphalt layer spreads the load due to its stiffness, which helps to dissipate the compressive strains to within the critical limits that can be sustained by the underlying granular pavement layers and the subgrade. The asphalt can also absorb the high shear stresses near the top of the pavement. High tensile stresses develop at the bottom of the asphalt layer, and must be controlled to prevent cracking and deterioration of the layer. These loads and strains are illustrated in Figure 3.1 below.

Thin-surfaced pavements have either chipseals or thin (less than 40 mm thick) bituminous mix surfaces. The thin surfacing layer adds no structural capacity to the pavement. The total pavement thickness is built up above the subgrade by placing and compacting layers of materials of increasing strength and quality. The granular cover over each layer must also be sufficient in depth to dissipate the stresses to a magnitude that can be sustained by the particular layer. Hence, the strength of a thin-surfaced flexible pavement is the result of building up of thick layers and thereby distributing the load over a greater area of the subgrade. Because the unbound granular basecourse is so close to the road surface, it is subject to high shear and normal stresses. The loading and strains for these pavements are illustrated in Figure 3.2.

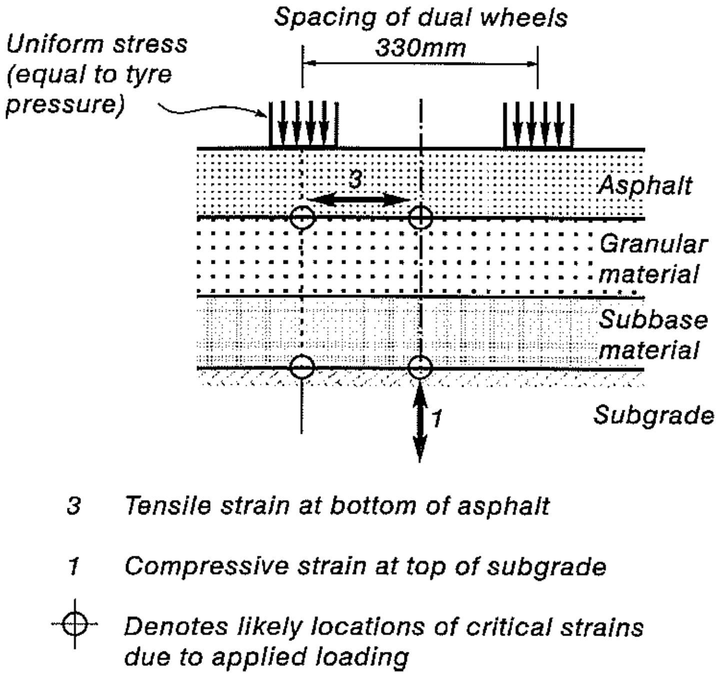


Figure 3.1 Critical strains in asphaltic concrete pavements.

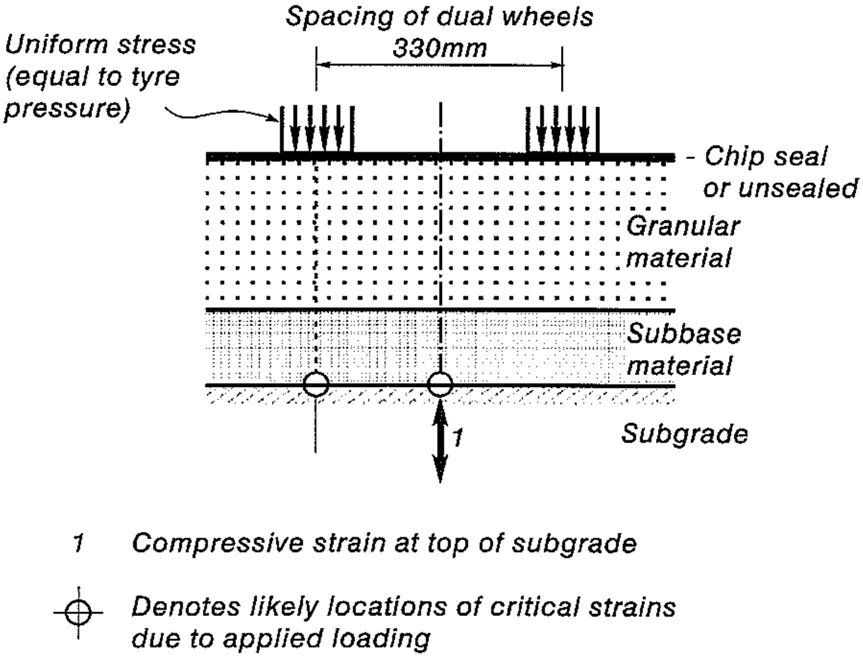


Figure 3.2 Critical strains in thin-surfaced unbound granular pavements.

The surfacing most commonly used in New Zealand is chipseal. Chipseals involve the application of bitumen directly onto unbound granular basecourses or existing surfacings, followed by a cover coat of uniformly sized, cubic-shaped aggregate (crushed stone or river gravel). The resulting layer is normally less than 25 mm thick, and adds no structural capacity to the pavement. The functions of a chipseal are to provide a low cost wearing surface, an impermeable membrane, and skid resistance.

Most pavements in New Zealand are thin-surfaced flexible pavements. The model for describing the behaviour of thin-surfaced, unbound granular flexible pavements is based on multi-layer linear elastic theory. It assumes that thin surface layers, of thicknesses less than 35 mm, do not contribute to the structural capacity of the pavement and the stresses are dissipated through the depth of the granular cover layers above the subgrade. The main criterion is to limit the vertical compressive strain in the subgrade to acceptable magnitudes, because the design theory presupposes that the primary mode of structural failure is permanent deformation in the subgrade. Other common modes of failure in unbound granular pavements include: shallow shear within the unbound layers, shoving along the edge of the trafficked lanes due to lack of shoulder support, as well as polishing of the stone chips in the seal coat, and bitumen bleeding to the surface leading to flushed surfaces and coincident low skid resistance in wet weather.

Virtually all the overseas research studying the influence of dynamic vehicle loading on the wear of flexible pavements involves thicker asphaltic concrete pavements. The thickness design of asphalt pavements is governed by two criteria: the subgrade strain described above, and the horizontal tensile strain in the bottom of the bound asphalt layer. The latter is supposed to be the main cause of cracking in the asphalt. The overseas literature tends to concentrate on asphaltic concrete pavements, which are relatively rare in New Zealand, and deformation, stresses and strains in the asphalt layer, which are not relevant to New Zealand roads for the same reason.

Another important difference between unbound granular and asphaltic concrete pavements is that the moduli of the former rely on the moisture content of the aggregate. When unbound aggregates are near or at saturation, the stresses from dynamic wheel loads are instantaneously transmitted through the granular cover to the subgrade, with only a minimal reduction in the magnitude of the stresses, because of hydrostatic pressures within the granular layers. In the normal situation with unsaturated pavement there is a reduction in stress with depth. Additional moisture in unbound granular pavements leads to higher porewater pressures closer to the surface, which reduces the effective strength of the pavement and leaves the pavement materials more susceptible to creep deformation under loading. The dynamic loads could also increase pumping of fines mixed with water through cracks in the surface seal, which detrimentally affects the strength of the basecourse, which is the main structural layer of unbound granular pavements.

All the research on flexible pavements reported in Cebon (1993), Gillespie et al. (1993) and OECD (1992) relied on theoretical studies or empirical studies of structural asphaltic concrete pavements and linear elastic theory to analyse pavement response. Also, the evaluation of the pavement damage resulting from fatigue and rutting focussed on stresses and strains in the top bound layer of asphaltic concrete pavement. The closest any of the pavements were to New Zealand practice was a 50 mm-thick asphalt layer used in some of Gillespie's theoretical modelling.

3.2 Stationary Wheel Loads

3.2.1 Tyre Configuration

Bonaquist et al. (1988) found that, at loads greater than legal loads and at increased tyre pressures, the detrimental affect of bias ply tyres on the fatigue of a flexible pavement is slightly greater than that of radial tyres. The shear stress distribution of radial and bias ply tyres may affect the pavement surface distress (Gillespie et al. 1993). The circumferential belt of radial ply tyres is supposed to reduce the shear stresses inherent in bias ply tyres. Bias ply tyres create an inward shear stress distribution in the contact area, which results from the toroidal shape of the tyre conforming to the surface, and thereby resist radial stresses. Radial stresses create material flow and rutting in the surface directly under the tyre, so the shear stress characteristics of bias ply tyres may reduce surface distortion. The effect on chipseals is unknown, but should serve to reduce chip loss.

Papagiannakis et al. (1987) collated research findings regarding the equivalent loads of wide-base single tyres and normal dual tyres, and concluded the loads vary significantly depending on the criteria used to compare the effects. Wide-base single tyres and conventional single tyres cause 2.1 and 2.9 times, respectively, as much pavement wear as dual tyres (OECD 1982), from research based on asphaltic concrete pavements. For an unbound granular pavement constructed to New Zealand specifications using local aggregate, a wide-base single tyre causes 1.9 times the rut depth created by dual tyres (Pidwerbesky & Dawe 1990). This test had each type of tyre carrying the same wheel load and running in its own track at a constant wheelpath position. (The surface rutting created in asphaltic concrete pavements under axle loading is highly dependent on tyre configuration.)

Rutting in asphalt is the result of plastic deformation within the asphaltic concrete, which is dependent on the magnitude and the duration of the load. Gillespie et al. (1993) used two criteria for assessing rutting damage under tyre loading: the maximum rut depth and the volume of material displaced. The latter was preferred because general depressions in the trafficked lanes are caused by the accumulation of rutting from numerous wheels running in different lateral positions. Comparing single and dual tyres carrying their rated loads, dual tyres produce up to twice the rutting volume because of the combined effect of the two tyres. For a wearing course thickness of 50 mm (the thinnest bound surface layer considered in the study), a surface temperature of 25 °C, and an axle carrying 7.3 t, the Equivalence factor of a 15R22.5 wide-base tyre is 0.61 (Table 11, page 34 in Gillespie et al. 1993). The Equivalence factor in this case was defined as the ratio of the rut volume caused by an axle with single tyres at their rated load, to the combined rut volume created under dual tyres on an 8.2 tonne axle (1 ESA).

Currently, pavement models cannot accurately determine the volume of material displaced by a tyre, primarily because the tyre contact shape is modelled as a circle.

3.2.2 Tyre Pressures

The tyre contact area, pressure magnitude and pressure distribution strongly affect the stresses and strains in and near the surface of a pavement, but the effect reduces with depth. When a tyre is rotating smoothly over a road surface with a constant vertical load, the general assumption in pavement design and analysis has been that the normal component of the contact pressure between tyre and road surface is uniform, acts over a circular footprint area, and equals the tyre inflation pressure. The region in the centre of the tyre imprint consistently maintained pressures within 15 psi (100 kPa) of the actual inflation pressure for all tests conducted by Marshek et al. (1986a). However, the peak contact pressure has been found to be more than twice the tyre inflation pressure (de Beer 1994; Tielking & Abraham 1992). Woodside & Liu (1992) have measured dynamic surface stresses and found them to be as much as twice the static value. This is significant because New Zealand roads are predominantly surfaced with chipseal coats, and polishing and breakdown of the stone particles in the seal could be exacerbated by the higher stresses.

Studies have shown that the contact pressures increase near the edges of the contact area, especially at either lateral side, due to the stiffness of the sidewalls and tread band. At the recommended inflation and loading conditions, the maximum edge pressure is typically twice the magnitude of the inflation pressure (OECD 1992). Also, doubling the axle load but keeping the inflation pressure constant resulted in a doubling of the subgrade compressive strain, and had little effect on compressive strain in the bituminous layers. The conclusion is that dynamic contact conditions will affect stresses and strains only in the upper layers, and that the overall dynamic force magnitude will have the greater effect in the lower layers.

Gillespie et al. (1993) reported that increasing tyre pressure resulted in increased stresses and strains within the pavement, thereby leading to deeper rutting because of the higher plastic deformation when the load is concentrated in a smaller area. Marshek et al. (1986b) used the BISAR computer program and the contact pressure data generated from the experimental work described in Marshek et al. (1986a) to calculate pavement strains. They determined that inflation pressure produced an extremely small increase (actually, the increase appears to be negligible considering the variability in the data) in the compressive strains developed at the top of the subgrade. Increasing the axle load increased the maximum compressive strain by a proportional amount, regardless of the surface course thickness. Bonaquist et al. (1989) compared the effects of tyre pressure on asphaltic concrete pavements and reported that tyre pressure does influence the fatigue equivalency factor for a particular load with respect to measured strains in asphalt-bound layers.

The general conclusions in Cebon (1993) were that fatigue damage related to tensile strain at the bottom of thin asphalt pavements increases rapidly with average contact pressure, and that inflation pressure has a negligible effect on subgrade rutting. However, Pidwerbesky (1992) has shown that, at the mid-depth of an unbound granular layer, elastic compressive strain actually decreased (in magnitude) as the inflation pressure increased, for the heaviest (46 kN) wheel load, with 5% level of confidence. In the subgrade, vertical compressive strain decreased (in magnitude) as the inflation pressure increased for all the wheel loads included in the test (21 to 46 kN), but the decrease was statistically significant (at the 5% level of confidence) under the 21 kN wheel load only.

The above results suggest that the strain in the lower unbound granular layers and top of the subgrade may be dependent upon the "zone of influence", which is related to load, contact area and speed of vehicle travel. Thus, when the speed is constant and the contact area is reduced through higher tyre inflation pressures, the zone of influence in the unbound granular layers and subgrade is reduced, thereby reducing the strains. The most likely implication of this phenomenon for dynamic wheel loads is that the effect of such loads on pavement and subgrade response is negated, at least with respect to tyre inflation pressures.

In general, tyre pressure causes relatively large stresses at and near the surface of a pavement, and the magnitude of the stress reduces with increasing depth. The shear stress induced by the combination of tyre pressure and dynamic loading is the most crucial aspect, and is especially important when the main structural component of the pavement is the unbound granular basecourse. With current New Zealand public highway specifications, unbound granular basecourses are produced with properties that resist shear within the materials, and should be adequate to resist the additional shear stresses caused by dynamic wheel forces. However, this last statement has not been conclusively proven.

3.2.3 Axle Load and Pavement Deterioration Relationship

The current New Zealand model uses multi-layer linear elastic theory for determining the equivalency factor for different tyre types, tyre inflation pressures, and axle configurations. Studies have demonstrated that the load equivalency exponents for flexible pavements depend on the type of pavement failure mechanism (rutting, fatigue cracking, or loss of serviceability), type of pavement (unbound granular basecourse, cemented basecourse or asphaltic concrete), and tyre-axle arrangement (number of tyres and axles, axle spacing, or tyre type). For example, Table 3.1 shows that the load equivalency exponent for single axles over flexible pavements ranges from 1 to 8, with a concentration of values between 2 and 6 (OECD 1988; Kinder & Lay 1988). However, these tests have considered only a limited number of vehicle characteristics, and the flexible pavements tested usually contained an asphaltic concrete structural surface or bound basecourse layers, both of which are uncommon in New Zealand highways.

A great deal of uncertainty still exists as to the load equivalency factors appropriate to New Zealand conditions. Saunders (1982) suggests that, for New Zealand highways, the fourth power relationship may be appropriate for pavements surfaced with structural layers of asphaltic concrete, whereas an exponent greater than 4 might be more appropriate for those containing cemented base/sub-base layers, and an exponent less than 4 might be more appropriate for unbound pavements. This implies a decreased sensitivity to heavy loadings for unbound pavements. (For the sake of simplicity, the fourth power has been used in all cases by the New Zealand highway authorities.) The first phase of resolving the problem is to identify the issues. Two separate but interdependent issues involve determining load equivalencies of different vehicles for input to:

- Models for pavement design and predicting pavement performance, and
- Models for comparing relative effects of vehicle characteristics.

Table 3.1 Load equivalency exponents for flexible pavements.

Country	Criterion	Exponent	Configuration
Australia	Cracking	2	dual and single-tyre
	Rutting	3.3 - 6	single axles
Finland	Fatigue cracking	3.3	dual tyre, single axles
		4	dual tyre, tandem axles
France	Fatigue cracking	2	dual tyre, single axle
	Rutting	8	dual tyre, single axle
Italy	Fatigue cracking	1.2 - 3	15 axle tyre configurations
USA	Serviceability	4.4	single axles
	Loss	4.9	tandem axles
	Rutting	4.2	single axles
		4.8	tandem axles
	Cracking	1.3 - 1.7	single axles
		1.9	tandem axles

The load equivalency factors for a pavement design model are not so critical. Pavement design is less sensitive to the number of ESA because other aspects, such as environmental and moisture conditions, can have a much greater influence. Research carried out in New Zealand on typical pavements indicates that, if the aggregate used in the granular layers possesses sufficient strength to resist traffic loadings and the drainage is adequate, then loss of serviceability will be caused primarily by subgrade deformation and not by aggregate deterioration (Bartley 1980). In other words, good quality crushed aggregate should survive a great number of load repetitions without appreciable deterioration.

Maree et al. (1982) reported that the moisture content of unbound granular bases has a significant influence on the traffic-carrying capability of the pavement and, in a dry state, such pavements can carry a large number of axle load repetitions, which has been confirmed for New Zealand pavements (Pidwerbesky 1989).

Both studies also showed that as soon as the granular layers become wet, the rate of permanent deformation increases markedly, though high quality crushed stone bases are less sensitive to water. Also, loading conditions will change over the pavement life regardless of the original model. Therefore, even though dynamic wheel loads can be substantial, it is unnecessary and impractical to incorporate dynamic wheel forces into the pavement design process.

3.3 Moving Constant Wheel Loads

3.3.1 Longitudinal Load Transfers

The main effect of longitudinal load transfers is to create higher axle loads in the lower axles on a gradient. Because New Zealand has a high proportion of relatively steep grades over much of the length of its road network, the longitudinal load transfer results in a significant increase in the total loading being applied. Also, for a given grade of bitumen possessing a particular viscosity at a specific temperature, the stiffness of the bitumen under loading is influenced primarily by its temperature on the road and the rate of loading. So, in a situation where a heavy vehicle is travelling uphill, the rate of loading is decreased which reduces the stiffness, and the bitumen will be more susceptible to the heavier load being applied by the trailing axle, leading to distress in the seal. Displacement of the stone chips or the bitumen itself can occur and, ultimately, the road has to be re-sealed sooner.

3.3.2 Transverse Load Transfers

Cornering and turning by heavy vehicles is especially detrimental to chipseals and the upper part of unbound granular pavements, because the sprayed seal has very little resistance to the lateral forces generated. As well the underlying aggregate has no tensile capacity to resist the lateral forces. Transverse load transfers can create high lateral shear forces in the surface layer, leading to shoving and edge failures in the basecourse, and edge breaks in seal coats. The latter is exacerbated by the lack of sealed shoulders and adequate shoulder support in many roads in New Zealand.

3.4 Moving Dynamic Wheel Loads

3.4.1 Effect of Suspensions on Pavement Wear (Sprung Mass Modes)

Gillespie et al. (1993) reported that the dynamic behaviour of suspensions has little effect on rutting damage in flexible pavements. However this conclusion is based on the assumption that the behaviour of flexible pavements is linearly elastic, which is inappropriate for unbound granular pavements, for reasons explained previously.

Considering only flexible pavements, the load-spreading mechanisms in thin-surfaced unbound granular pavements are different from those in asphalt pavements because the former are more dependent on conditions at the road – tyre interface. Thus, when the effects on pavement strains of suspension type and dynamic loads are coupled, thin-surfaced unbound granular pavements are particularly at risk (OECD 1997).

It has also been reported that spatial repeatability (based on the concentration of dynamic wheel loads at the same location on the road because of heavy vehicles having similar sprung mass characteristics and moving at the same speed) is significant for all types of pavements.

Where the composition of the truck traffic flow tends to be similar, the risk of pavement damage from spatial repeatability is even greater (OECD 1997). Therefore, given the prevailing truck traffic and pavement design in New Zealand, the road network is vulnerable to damage caused by the sprung mass modes.

3.4.2 Vehicle Factors Affecting Dynamic Wheel Load and Road Wear

The effect of speed on pavement deflection was first measured in the AASHO Road Test (AASHO 1962). The amplitude of the peak surface deflection decreased as the speed increased. Cebon (1993) assumes the strain amplitude within the pavement is directly related to the amplitude of surface deflection, which is invalid for unbound granular pavements. He then concludes that the speed effect is important when considering the road damage caused by tyre forces, because pavement fatigue is sensitive to strain amplitude. At higher speeds, the wheel load passes over a specific point in the pavement more quickly, reducing the time available for plastic deformation to occur. Gillespie et al. (1993) report that rut depth varies inversely with speed because the pavement loading time, which affects rutting, varies inversely with speed.

Steven (1993) measured subsurface pavement strains in a road under a variety of loads. The static axle loads ranged from 8 to 16 tonnes and the test speeds varied from 5 to 60 km/h. The results showed that the peak vertical compressive strain was related to axle weight on a linear basis, in both the subgrade and the basecourse. Analysis of the strain versus vehicle speed showed that the strain in the basecourse decreased as the speed increased, which agreed with the findings of Brown & Pell (1967). However, the strain in the subgrade increased as the vehicle speed increased, and this contradicts the findings of these authors.

3.4.3 Pavement Factors Affecting Dynamic Wheel Loads

Theoretical modelling and experimental work has shown that heavy vehicles of similar dimensions and suspension configuration produce similar dynamic load history traces (Cole 1990; Gyenes & Mitchell 1992). A disturbance in the pavement surface (pothole, localised high or low spot) will cause a perturbation to the suspension system of the vehicle. Downstream of the disturbance, clustering of the peak dynamic wheel loads occurs. Gyenes & Mitchell (1992) showed that this happened on both the TRL (Transport Research Laboratory UK) test road and on sections of public roads. Huhtala et al. (1992) showed that for repeated measurements of the same vehicle over a section of road, the peak dynamic wheel loads occurred at the same places. Huhtala et al. also showed that a vehicle travelling over the same section of road at different speeds had peak dynamic loads occurring at the same locations. Eisenmann (1975) proposed that the points of high dynamic loading were distributed randomly along the road. If this were the case, then the pavement would deteriorate uniformly, with respect to the accumulation of wheel loads. Since all heavy vehicles are not similar in suspension characteristics, there is some basis for this assumption.

3.5 Modelling Pavement Response to Loading

Basic requirements of analytical models for relating distress to performance are:

- The pavement models must be able to predict both the type and the degree of distress that will occur under any given set of conditions;
- The model must be able to predict the component effect of any particular form of distress on the primary output of the pavement (its serviceability–age history);
- The effect of various maintenance strategies on the serviceability–age history of the pavement must also be modelled.

Pavement response to traffic load models range from simple empirical models to sophisticated behavioural-response mechanistic models.

3.5.1 Modelling Pavement Materials with Non-linear Stress/Strain Characteristics

Most of the development work concerned with the use of theoretical analysis in flexible pavement design, is concentrated on accurate modelling of the asphalt layer. Resilient characteristics of pavement materials are normally specified in terms of a modulus of elasticity and Poisson's ratio. Simplifying assumptions are often made concerning the properties of the unbound granular layer and subgrade soil. These are a reflection of the relative states of knowledge concerning the various materials, together with the need to produce design methods that are not unduly complex. Also, unbound granular aggregates and cohesive soils exhibit non-linear stress-strain characteristics.

Theoretical and experimental work by Brown & Pappin (1985) and Pell & Brown (1972) have shown that non-linear elastic behaviour of granular materials and of cohesive soils is only of importance in pavements with thin asphalt surfacings. In these pavements the granular base layer is significant structurally, and its response primarily dictates the overall behaviour of the pavements. This is exactly the case for New Zealand pavements. Brown & Pappin (1981) concluded that linear elastic layer systems are inadequate for computing stresses within the granular layer.

Current pavement modelling techniques are inadequate to provide for dynamic wheel forces, mainly because the effective stress state of the pavement and subgrade materials under loading cannot be accurately defined. As modelling of pavements becomes more accurate, the speed of computers increases and quality of user-friendly programs improves, non-linear stress-strain characteristics of subgrade soils and unbound granular materials can be incorporated, and the impact of dynamic wheel forces can be accommodated.

3.5.2 Characterising Pavement Materials

In order to correctly model a pavement's response to loading, the material parameters must be able to be quantified. Analytical or mechanistic models require a direct measure of material strength and ability to withstand repeated loading. The most common test to determine the strength of a material is the repeated dynamic load or triaxial test. Depending on the way this test is carried out, either the strength (resilient modulus) or the ability of the material to withstand permanent deformation (rutting) is determined.

For granular materials, Thompson & and Smith (1990) showed that a permanent deformation test gave a better indication of the performance of the material than the resilient modulus test. In other repeated load tests, cohesive subgrade materials have been shown to withstand large numbers of repeated load applications if the applied load is kept below a predetermined threshold value (Raad & Zeid 1990). This threshold value is determined by laboratory tests. The rate of deformation decreases as the number of applied loads increases to a point after which permanent deformation stops. If the level of applied load is above the threshold level, then the permanent deformation increases to the point where the material fails. Other work has been done in New Zealand and overseas, but none of it addresses the specific problem of incorporating the effect of dynamic loading on the pavement.

Characterisation of pavement materials is very difficult, and substantial work has been carried out to develop appropriate repetitive loading techniques for different materials, but no existing technique is suitable for simulating the impact of dynamic loading.

3.5.3 Validity of Pavement Response and Vehicle Loading Models

Gillespie et al. (1993) state that the analytical methods for predicted pavement damage are not well validated, and found that the emphasis on strains at the bottom of bound surface layers, as an indicator of fatigue, is not justified, based on field observations. The latter statement is supported by research conducted in New Zealand (OECD 1997). Pavement deterioration and axle load are related by a power law, but the value of the exponent ranges from 2 to 6. The value has a major influence on the damage attributable to vehicle loading because, with a lower value, gross vehicle weight becomes the most important factor, and with a higher value, maximum axle load is the critical factor (Gillespie et al. 1993).

Contrary to the major assumptions of the multi-layer linear elastic theory and computer programs discussed earlier, the behaviour of materials most commonly found in New Zealand pavements, i.e. unbound aggregates, tend to be non-linear, elasto-plastic, non-homogeneous and anisotropic. The non-linear behaviour of unbound granular layers means that the modulus depends on the stresses induced in that material by the load being applied, and is therefore difficult to model. Because of non-homogeneity, the properties of adjacent samples of the same material can vary significantly. Due to anisotropy, the stresses and strains depend on direction, so the loading must be modelled properly. The input to most of the computer programs is limited to a circular loaded area and uniform contact pressure. A more suitable model would allow for different characteristics and dynamics of the suspensions, tyres and axles, such as tyre construction, stiffness, footprints and inflation pressures, and the sprung/unsprung masses. Another major limitation of multi-layer linear elastic theory is the inability to model pavement behaviour near the edge of the pavement. Because edge failure is a common occurrence in unbound granular pavements, the models should incorporate edge conditions which would then allow a more thorough determination of the wearing effect of dynamic wheel loads as they encroach on the edge of the trafficked lane.

In the past, the basic concept of pavement behaviour in New Zealand was developed on the underlying assumption that the basecourse properties are specified to sustain shear stresses and compressive strains. The primary mode of failure was to be subgrade deformation because this is less expensive to repair than cover failure, but the pavement still has to be of sufficient depth to protect the subgrade. Many existing basecourses may be substandard but have not failed because of the limits imposed by road controlling authorities on loading conditions. However, the higher stresses created under dynamic loading may cause shear failure in the basecourse, depending on the properties of the aggregate.

The sensitivity of the response of unbound granular layers to increased load caused by moving dynamic wheel loads, as compared with moving constant wheel loads and stationary wheel loads, is unknown.

Loading and pavement behaviour models that incorporate such aspects as dynamic pavement – vehicle interaction, tyre types and pressures, and non-linearity of unbound granular layers' moduli, should be developed. It is desirable to be able to more accurately represent the dynamic interaction of modern vehicles and unbound granular pavements because of the unique system of road user charges.

3.6 Asset Management

Because the primary operating characteristic of a pavement is the level of service provided to the users at a certain time, road authorities must:

- measure and evaluate the level of service to establish the current status of a pavement, and
- predict the change in level of service in the future, for either an existing pavement or for a pavement to be constructed, under the cumulative effects of traffic and environmental factors.

The rate of change in the level of service, or serviceability, depends on factors such as axle loads, tyre types and pressures, pavement type and thickness, surface distress, original construction quality, climatic factors, and maintenance performed.

Roading engineers and managers require a better understanding of the relationship between dynamic loading conditions and the fundamental response of the subgrade and unbound granular pavement layers to that loading, in order to produce better prediction models.

To reduce the total combined costs of the road users and the roading authorities, pavement management practices that programme maintenance and rehabilitation are being implemented. However, before dynamic loading characteristics can be considered in any asset management system, more accurate data on vehicle loads are needed so that the actual performance of a pavement can be compared with the predicted performance. An accurate pavement performance model needs to be developed and used to predict when deterioration reaches a critical level. Thus preventive maintenance can be scheduled and, thereby, reduce costs because by the time that pavement deterioration manifests itself as a pothole or a rut, the remedy is quite expensive.

The second issue, the axle weights and loading model, requires substantially more research, in order to determine load equivalency factors for allowable axle weights for different tyres and vehicles and for constructing a road user charges allocation model. For these models, linear elastic theory is unsuitable for evaluating the relative effects of different vehicles. Also, the models must take into account whether the major pavement criteria is:

- incremental damage, which is related to level of service, or
- total pavement life, which is related to performance.

Load equivalency conversion factors for incorporating the additional pavement wear caused by dynamic loads should not be based on cumulative loads to failure. The relationship between pavement condition and cumulative loadings is constant over most of the pavement life, and thus the marginal effect of an incremental increase in load varies depending on the road condition.

In addition, research has suggested that greater pavement deterioration occurs where localised weak spots in the pavement and peak dynamic wheel forces coincide (OECD 1997). Thus, any definition of functional failure should consider the concentration of localised failures and the relationship with spatial repeatability of dynamic loads.

4. Regulatory & Policy Options

4.1 Introduction

Essentially five mechanisms are available to reduce the impact of the vehicle-generated influences on pavement wear. These are

- regulation,
- road pricing,
- pavement design,
- maintenance management, and
- education.

The appropriateness of each of these mechanisms depends on which particular influence on pavement wear is being ameliorated as well as implementation, economic and political factors. The following discussion is limited primarily to technical and implementation issues. Political and wider economic implications are not investigated.

4.2 Regulations

Regulations are already used to control some of the pavement-damaging characteristics of heavy vehicles. The axle load regulations are a prime example. Axles fitted with ordinary single tyres and wide-base single tyres have lower allowable maximum weights than axles fitted with dual tyres. Axle groups have lower limits than the same number of single axles and so on.

From a theoretical point of view, these regulations could be seen to be unnecessary because the road user charges system (section 4.3 of this chapter) could charge the operators of these vehicles for the damage they cause, and so the system should be self-regulating. However, the road user charges are based on gross vehicle mass and assume that this load is distributed across all the axles optimally, which in practice is not necessarily so. The regulations provide an upper limit on the deviation from this optimal distribution.

One aspect of the current regulations, which appears to be at variance with the previous discussions, is the load limits on axle groups and their dependence on spacing. The consensus seems to be that the axles of a group do not cause significantly more damage in either rutting or fatigue, than the same number of widely spaced single axles carrying the same load on flexible pavements. Also within the normal range, axle spacing has no significant effect.

For New Zealand-style thin-surface pavements, the primary failure mode is rutting. The rutting mechanism is similar to that of flexible pavements and so this finding should also apply. If this result is accepted then, for road damage considerations, the axle load regulations for groups could be eliminated. Axles in groups could carry the same loads as the corresponding single axles, and there would be no loading advantages for wider axle spacing. Tyre wear considerations would encourage operators to have axles as closely spaced as practicable which would also reduce the surface scuffing effects of axle group. However, these limits also exist to meet the requirements of the bridge formula, and thus the implications for bridges need to be assessed before making any changes to regulations.

Other regulations that affect road damage are the gross vehicle mass limits and some of the suspension regulations. The gross vehicle mass limits do not exist to limit road wear. They are needed to protect bridges and for safety reasons. The suspension regulations require that, for axle groups, there is no mixing of suspension media, and that the suspensions have a static load-sharing mechanism. This load-sharing requirement is important for limiting road damage.

Within the current vehicle fleet the main problem associated with load-sharing mechanisms is with walking beam suspensions. These are designed to have good static load-sharing capabilities (though some researchers have expressed doubts as to their performance in this regard as well) but the mechanism is usually only lightly damped. This leads to a bogey pitch resonance mode at 8-10 Hz, which can generate high dynamic wheel loads on the pavement. This problem can be resolved with the addition of damping. Some modification of the regulations on load-sharing mechanisms to eliminate this problem, possibly by specifying a performance standard, would be beneficial. Mixing suspension media within an axle group does not inherently cause any problems. However, it causes difficulties for regulators in assessing the suspension's performance. At present this requirement can be waived if the suspension is tested to meet a set of performance standards. These are quite loose in that the testing requirements are not specified in any detail. The restrictions on mixed media suspensions could be lifted if a set of performance standards for all suspensions was defined. The downside of this is that there would be compliance costs for all vehicle and suspension suppliers.

Finally, consideration needs to be given to whether any new regulations could be used to promote road wear reductions. Tyre inflation pressure is a factor in pavement wear. It is more important in fatigue damage than for rutting but is still significant. For single tyres the impact of increased inflation pressure is higher than for dual tyres, while for dual tyres unequal inflation pressures can have a substantial negative effect. Regulations could be implemented to impose maximum tyre pressures and limits on the difference in pressure between tyres in a dual pair, but implementation and enforcement would be difficult. It is probably more effective to use education to promote improved tyre inflation practices.

4.3 Road User Charges

Road user charges are part of a road pricing mechanism developed in New Zealand to charge users for the costs incurred in their use of the road network. Road user charges apply to all heavy vehicles and to light powered vehicles not using motor spirit, LPG or CNG. The costs incurred in maintaining the road network are divided into three components:

- driver-imposed costs (signs, markings, etc.),
- space-imposed costs (capacity and speed improvements, etc.), and
- strength-imposed costs (strengthening, pavement wear, etc.).

The annual maintenance budget is allocated to these three components which are then proportioned between those vehicles subject to road user charges and those not. Road user charges are then set to recover this cost. A detailed description of this process is presented by Kennaird (1979) and by Fisher (1986) but the basics are relatively simple.

The driver-imposed costs are allocated on a per km basis independently of weight. Unpowered vehicles (trailers) are not allocated any of these costs.

The space-allocated costs are based on kilometres travelled and vehicle units that are related to licensed weight. The vehicle unit values were calculated by Kennaird (1979) using the formulae:

- $0.86 + G/7$ for powered vehicles, and
- $G/7$ for unpowered vehicles,
  where G is the licensed gross weight in tonnes.

This function has been chosen so that a passenger car with a nominal G value of 1 tonne is one vehicle unit, and heavy vehicles as a group have an average value of approximately 3 vehicle units.

Finally strength-related costs are allocated on the basis of the fourth power law. Two assumptions are made in doing this. The first is that the vehicle's gross licensed weight is distributed between the axles in order to minimise the road wear generated. The second relates to the average loading on which the calculation is done, and there is a contradiction between Kennaird (1979) and Fisher (1986) on how this is done. Kennaird says that it is assumed that for 50% of the distance travelled the vehicle is fully loaded, and that for the other 50% it is empty and operating at its tare weight. Fisher also says that it is assumed that the vehicle is fully loaded for 50% of the distance, but that for the remainder of the distance the load ranges between the tare weight and the nominated gross weight.

Using Kennaird's approach the following equations can be written to calculate the road user charges (RUC) per 1000 km:

For powered vehicles:

$$RUC = P_{driver} + 0.86P_{space} + 0.5P_{strength}\left(\frac{t}{G_{std}}\right)^4 + \frac{P_{space}G}{7} + 0.5P_{strength}\left(\frac{G}{G_{std}}\right)^4 \qquad \text{Equation 1}$$

For unpowered vehicles:

$$RUC = 0.5P_{strength}\left(\frac{t}{G_{std}}\right)^4 + \frac{P_{space}G}{7} + 0.5P_{strength}\left(\frac{G}{G_{std}}\right)^4 \qquad \text{Equation 2}$$

where	P_{driver}	is the driver costs per 1000 km travelled
	P_{space}	is the space costs per vehicle unit per 1000 km travelled
	$P_{strength}$	is the strength costs per ESA per 1000 km travelled
	t	is the nominal tare weight for the vehicle type
	G_{std}	is the gross vehicle weight that, for the vehicle type, generates one ESA
	G	is the gross vehicle weight

Both these expressions consist of a term or terms that are independent of licensed weight, a term that is linear with licensed weight, and a term that is a fourth power of licensed weight. Clearly as the licensed weight increases, the fourth power term becomes more and more dominant.

Fisher (1986) makes the point that, although there may be some debate over the validity of the exponent in the fourth power law, changing the power to 3 or 5 is not highly significant because the strength component of costs would still be almost totally allocated to heavy vehicles. As the road user charges system must still collect the total revenue required to meet the total costs, changing the exponent in the power term would result in a corresponding change in the cost coefficient ($P_{strength}$ in the above equations) in order to achieve the same total revenue. While this argument is valid as far as it goes, changing the exponent in the power law that governs pavement wear would significantly change the relative road user charges rates for different vehicle configurations. This might well have a significant influence on the composition of the fleet.

As an example, and at the simplest level, compare vehicle type 30, the two-axle trailer, with vehicle type 37, the three-axle trailer. Using current road user charge rates for 17 tonnes licensed weight, the type 30 vehicle incurs over 2.5 times as much RUC as the type 37 vehicle.

From Equation 2 for RUCs for unpowered vehicles, we see that the constant term and the fourth power term are both related to the strength costs, while the linear term is a function of the space-related costs. By applying a fourth order polynomial regression fit to the RUC tables, a good fit is obtained and provides estimates of the coefficients of the various terms. If the space-related costs (linear term) are subtracted, the ratio of the remaining costs, which are all strength-related, is 3.57. Using the coefficients calculated from the type 30 RUC tables and a value for G_{std} of 13.79, we obtain a value for $P_{strength}$ of approximately 272.7 and a tare weight (t) of 2.84 tonnes. This implies a G_{std} for the type 37 vehicle of 18.97 tonnes and a tare weight of 3.54 tonnes. These values for G_{std} and t are reasonable.

Using a third power law requires the coefficients to be adjusted so that the same total RUCs are collected. Applying this principle to the type 30 vehicle at 17 tonnes licensed weight, we find that the required coefficients are G_{std} equals 13.02 tonnes and $P_{strength}$ equals 279.9. If these values are used for the type 37 vehicle we calculate a corresponding G_{std} of 17.31 tonnes. From this we can calculate the RUCs for 17 tonnes licensed weight. The result is that the type 30 vehicle is now only 1.93 times as expensive in RUCs as the type 37.

Raising the power to 5 would have the opposite effect, increasing the difference in RUCs between the two configurations. From an operational point of view, the type 30 vehicle is more efficient, having a lower tare weight and fewer axles. It may also have benefits for the pavement surfacing, as axle groups tend to cause higher shear loads on the surface than single axles.

The example considered here is a very simple one, looking at the choice between a two-axle and a three-axle trailer. In practice however the situation is far more complex. Changes in the road user charges structure may cause changes to operators' views on which vehicle combinations and configurations are favoured. The price-elasticity of these decisions with respect to RUCs would form the basis of a substantial study in itself and is beyond the scope of this work. The main point to be made is that magnitude of the exponent in a pavement wear model could have a significant impact on the makeup of the heavy vehicle fleet in New Zealand.

Kennaird (1979) suggests there is some evidence for using a higher power than four on roads constructed for light traffic. As mentioned in section 3.2.3 of this report, other evidence suggests that a lower power value might be more appropriate for unbound pavement structures. Although it is not possible at this stage to specify an alternative value for the exponent, it is important to note that changing this will have an influence on the composition of the heavy vehicle fleet. Such a change will not have much effect on the total pavement wear caused. It will primarily influence how the costs are allocated to different vehicle tyres. The total level of RUCs would be virtually unchanged. (Small changes may occur if the change in RUC rate encourages the use of different vehicles with proportionately higher or lower tare weights.)

One vehicle-generated influence on pavement wear that could be incorporated into the RUC structure is the use of road-friendly suspensions to reduce dynamic wheel loads. For a complete implementation it is necessary to be able to assess suspensions for their performance with respect to "road-friendliness" and to ensure that they maintain this performance in-service. This problem has been investigated by the OECD DIVINE project (Woodrooffe 1997), with complementary research in New Zealand (de Pont 1993, 1996, 1999).

Three methods of suspension assessment have been proposed, tested and found to be suitable. Any or all of these techniques could be implemented in New Zealand. The results of these tests rate the suspensions in terms of the dynamic loads they generate. However, any RUC discount must primarily reflect the reduction in pavement wear that will result. Gillespie et al. (1993) have suggested that, for flexible pavements, the difference in fatigue damage caused by "good" or "poor" suspensions is between 25% and 50%. They also suggest that the impact of dynamics on rutting is small.

However, as pointed out in section 3.4.1 of this report, the linear elastic models used are not valid for unbound pavements. A conservative approach might be to give road-friendly suspensions a 10% differential in the strength component of their RUCs. To maintain current revenue, this would involve increasing the value of $P_{strength}$ slightly for all vehicles and then reducing this value by 10% for vehicles with road-friendly suspensions. The level of increase required depends on the current proportion of vehicles fitted with road-friendly suspensions. If this were 10% of the fleet, it would only be necessary to raise $P_{strength}$ by 1%. At higher axle loads the strength component of RUCs is up to 80% of the total, and thus the level of reduction in RUCs would be around 8%. Whether this is sufficient to encourage operators to change their choice of suspensions is unknown.

4.4 Pavement Design Options

Road geometry contributes significantly to load transfers within the vehicle, and these in turn generate increased levels of pavement wear. Many of these road geometry features are unavoidable as, for example, braking, acceleration and gradients all cause longitudinal load transfers. In general the road layout design has already tried to minimise the impact of these factors and there is nothing further that can be done. However, pavement designers should be aware that these result in load transfers occurring within the vehicle that will cause increased damage. There are benefits to the system if the pavement design is strengthened in these regions to compensate for the higher loads.

Various policy options can be considered in specific projects where dynamic loading could be expected to be much greater than the average, in order to minimise either moving dynamic wheel loads themselves or the effect of such loads. These include constructing pavements with thicker granular layers, requiring the surface profile of new or rehabilitated constructions to be of a higher standard than normal, and optimising cross-slope.

Similarly transverse load transfers occur because of camber, cross-slope, and cornering. Increasing the strength of the pavement in locations where load transfer is a factor would improve the life of the pavement as a whole.

Because dynamic loads can be substantially greater than the static loads, if traditional load equivalency conversion factors are applied to the dynamic loads, the resulting dramatic increase in numbers of repetitions of equivalent standard axles implies that pavement wear is increased and, correspondingly, pavement thicknesses must be increased. Given the spatial repeatability in the normal traffic stream, only specific "hot spots" (localised occurrences of high dynamic loadings) will need to be strengthened. Increasing the thickness of an entire section of road would most likely be a waste of funds. Even though dynamic wheel loads can be substantially greater than the static wheel load, it is unnecessary and impractical to incorporate dynamic wheel forces in the pavement design process. However, maintenance management strategies can be modified to incorporate such knowledge of dynamic loading.

4.5 Maintenance Management

Historically, New Zealand has applied a pavement design and maintenance strategy of low capital cost at construction. The penalty is increased maintenance activity during the life cycle of the pavements. Unbound granular pavements with chipseal coats are the predominant type of road structure because such pavements are less expensive to construct, and repairs to localised failures are less expensive, compared with asphaltic concrete pavements. This strategy was deemed to best suit the environmental, traffic and fiscal conditions during a time of rapid expansion of the economy and the sealed road network. In practice, maintenance activities occur relatively often, which substantially increases both the costs to the users and the cumulative life cycle costs to the road controlling authorities.

The above strategy encourages higher dynamic loads on the road pavements because localised failures caused by the infiltration of water and other factors, are more likely to occur in granular pavements. The strength of the underlying pavement layers is very dependent on the permeability of the thin film of bitumen in the seal, and the latter is easily distressed. Quality control in maintenance activities and trench reinstatements is often compromised for the sake of economic "efficiencies", so the repairs are also prone to early deformation and deterioration, which creates disturbances in the road profile.

Maintenance consumes the greatest portion of road controlling authorities' budgets. Thus maintenance management has become increasingly important, and maintenance management strategies significantly influence the efficient utilisation of available resources in providing a desirable level of service. Maintenance management strategies that take advantage of information about vehicle dynamics should be established so that maintenance intervals could be changed in relation to the occurrence of hot spots and the accumulation of equivalent standard axles caused by dynamic loading. The different effects of changes in static and dynamic loads on maintenance and rehabilitation measures must also be considered. The maintenance management strategy would have to be flexible in order to take into account various measures, including pavement construction type, pavement condition and traffic, maintenance types and intervals, relative costs of the activities and age of the structure. Maintenance decisions would have to be based on road condition and traffic data that are related to dynamic loading, such as longitudinal profiles and vehicle types (OECD 1992).

Improved maintenance management strategies and quality assurance practices could reduce the dynamic loading and, thereby, reduce the road wear.

Figure 4.1 illustrates how the cumulative level of service, which in this case can be defined as roughness, can vary greatly during the life cycle analysis period depending on the maintenance strategy adopted. Lower levels of service or greater roughness induces dynamic wheel loading, which in turn can induce localised failures, leading to increased roughness and the cycle continues. This can be described as a positive feedback loop.

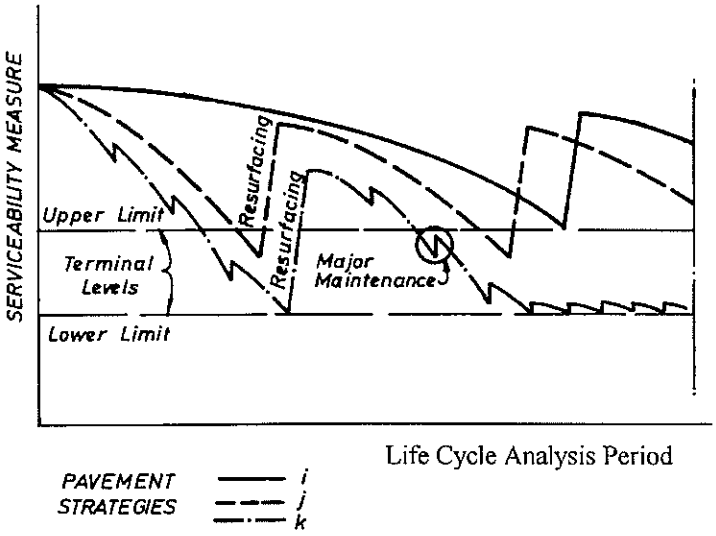


Figure 4.1 Pavement performance under three different maintenance strategies.

4.6 Education

An important factor in pavement wear, which is not very amenable to regulation or incentives, but could be attained through education of road users, is the issue of tyre pressure. The biggest problem in this area is the uneven inflation of tyres in a dual set. Anecdotal evidence is that this is a widespread phenomenon in the NZ vehicle fleet and elsewhere. In the extreme, the result is that the dual tyre set behaves almost as a single tyre. This can increase the road damaging effect of this wheel by a factor of three or more. The operator obtains no benefits in this situation and increased tyre wear will occur as a result. The problem occurs primarily because of the awkwardness, in many instances, of checking the inflation pressure on the inner wheels.

The other tyre pressure factor is that of using appropriate inflation pressures for the tyre loads. Incorrect and in particular over-inflation of tyres tends to cause increased pavement wear. Although Gillespie et al. (1993) found this influence on pavement wear to be relatively small, it is desirable to encourage operators not to over-inflate their tyres.

Historically, engineers and other professionals involved in providing and managing road networks have ignored dynamic loading in technical and policy decisions, primarily because of the lack of information about the influence of dynamic loads and because pavement performance models could not accommodate dynamic loading. Road network managers should be made aware of the financial and management implications and benefits of incorporating dynamic loading into the relevant design, construction and maintenance strategies.

5. Conclusions & Recommendations

Factors that affect pavement wear are:

- static axle load
- tyre configuration
- tyre pressures
- longitudinal load transfers due to gradient, acceleration and braking
- transverse load transfers due to camber, cross-slope, and cornering
- suspension load sharing
- suspension dynamics

Most of the overseas research findings on pavement wear are based on either rigid Portland cement pavement structures or flexible asphaltic concrete structures. The most widely used pavement in New Zealand however is an unbound structure coated with a thin surface, the primary purpose of which is waterproofing and to provide a running surface. It has often been regarded as a thin flexible pavement but, in fact, it does not strictly behave like this. The fatigue cracking failure mechanism used in flexible pavement analysis does not occur for these pavements and the rutting mechanism is different in that no rutting in the surface layer is involved. Therefore the direct application of the results of overseas research to these pavements is flawed. However, although local research results relate to specific aspects of pavement wear and response, no models are sufficiently well developed to be able to replace the overseas data. Therefore it is necessary to use these overseas data but the limitations of doing so must be kept in mind.

Static axle loads

Static axle loads are the main contributor to pavement wear. As these are primarily determined by the payload and tare weight, the options for reducing these are limited. However there are measures that could be implemented to lessen the pavement wear. For example, there appears to be no reason why axle groups should be limited to lower loads than the same number of single axles. Relaxing this regulation would encourage tandem axles to be placed close together (the current regulations allow them a greater maximum weight if they are more widely spaced). This would reduce tyre wear and surface scuffing of the pavement. A check on the implications for bridges is needed before this could be implemented.

Tyre configuration

The issue of tyre configuration is already addressed in the present RUC structure. For example, comparing a type 27 vehicle (a two-axle trailer with single tyres) with a type 30 vehicle (the same trailer with dual tyres) the RUCs for the type 27 are up to two times larger than type 30.

Tyre pressures

Tyre pressures in general have only a relatively small effect on pavement wear. However, unequal inflation of dual tyres can have a large effect. The best way to address this issue would appear to be through education of road managers and operators, because regulations would be difficult to enforce and incentives are not appropriate. Also it is in the operators' best interests to have correctly inflated tyres.

Load transfers

Load transfers related to road geometry and acceleration, cornering and braking are unavoidable. However, they should be factored into pavement design procedures. By reinforcing the most vulnerable parts of the pavement network, the performance of the system will improve.

Suspension dynamics & load sharing

Suspension dynamics are a factor in increased pavement wear and their performance could be improved through regulations and alterations to the RUC structure. The regulations relating to suspension load sharing could be tightened to define specific performance standards and the test procedures to evaluate them. The best mechanism for encouraging the use of more "road-friendly" suspensions is through modified RUCs. At the present time, techniques for assessing suspension road-friendliness have been developed but not yet implemented anywhere in the world.

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