The Impact of Small Diameter Tyres on Pavement Wear

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Contents

Executive Summary

1. Introduction

Small diameter tyres are being used increasingly in heavy vehicle applications to help resolve difficulties with the transport of either particularly heavy or tall loads. Axles fitted with small diameter tyres (R19.5 and R17.5) are significantly lighter than those fitted with standard tyres, and this saving in tare weight translates directly to additional load capacity. Similarly the use of small diameter tyres enables vehicle designers to reduce the vehicle-load height allowing taller loads to be carried without violating the legal height requirements. However, there is some speculation that the use of these tyres, which operate at higher inflation pressures and have a smaller contact patch, might generate increased levels of pavement wear. The study described in this report and carried out between 1996 and 1997 addresses this issue and makes some quantitative assessments of these effects.

The use of small diameter tyres could be expected to change the interaction of the vehicle with the pavement in two ways, broadly described as tyre contact effects and vehicle dynamics effects. Small tyres require higher inflation pressures to carry the same load, which also means that the contact patch area of the tyre is reduced. In addition, the contact pressure distribution of a tyre is not uniform and whether this distribution is different for small tyres was investigated.

The vehicle dynamics changes come from two sources: axles fitted with small diameter tyres have a lower mass, and the tyres are expected to have a higher stiffness. Both these factors will alter the dynamic behaviour of the vehicle and hence the level of dynamic wheel forces applied to the pavement. To complete the picture the effect of these changes in vehicle – road interaction on pavement wear was then assessed.

2. Literature Review

The first stage of the study was a literature review to determine whether these issues had previously been investigated. Only one previous study had done any work in this area and even then only to a very cursory level. Local tyre suppliers were approached and were very helpful in providing data sheets for their tyres. Based on these data, the 11R22.5 tyre was used as the standard tyre for the comparison and the 235/75R17.5 tyre as the small diameter tyre. This is the smallest tyre that can be operated at the full range of legal axle weights. Both tyres were inflated to the manufacturers' recommended pressures. However, in reviewing the manufacturers' data, it was discovered that the recommended inflation pressures for the standard size tyres at New Zealand axle load limits were considerably lower than those believed to be commonly used. For this reason a standard size tyre inflated to 690 kPa (100 psi) was also used for the comparisons.

3. Tyre-Contact Patch Size Effects

The effect of using small diameter tyres on the tyre-contact patch size and pressure distribution was determined next. Very limited data were available for small diameter tyres because, not surprisingly, the studies concentrated on the most commonly used tyre sizes. However, using the data that were available, reasonable inferences could be made about the likely behaviour of small diameter tyres.

4. Vehicle Dynamics Effects

To determine the vehicle dynamics effects, computer simulation models were used. It was found that the two vehicle dynamics factors had opposite effects. Reducing the unsprung mass reduces the dynamic wheel loads, while increasing the tyre stiffness increases them. Overall, the effects are very small and the impacts on pavement wear are negligible.

5. Implications for Pavement Wear

The implications on pavement wear, as already mentioned, of the changes in vehicle dynamics are negligible. Pavement response modelling software was used to determine the impact of tyre-contact patch size and pressure distribution on the peak compressive strains in the pavement layers. From these strains the expected impact on pavement wear was calculated.

6. Summary

The findings of this study are as follows:

- The use of small diameter tyres does not have a significant impact on dynamic wheel forces, and consequently on the pavement wear caused by dynamic wheel forces.

- With a pavement design that is typical for New Zealand roads, the use of small diameter tyres will generate peak compressive strains in the subgrade which are around 5% higher than those generated by a correctly inflated standard sized tyre. Based on the model used for pavement design, this would correspond to an increase in pavement wear of around 21%.

- If the standard size tyre is over-inflated for its load (which may be common practice), it will, on the same pavement, generate peak compressive subgrade strains which are around 2.5% greater than those generated by the correctly inflated tyre. Furthermore, if the change in contact pressure distribution is taken into account, these strains could be up to 2% greater again. This is very similar to the situation with small diameter tyres.

- Over-inflating small diameter tyres will similarly have a detrimental effect on subgrade strains and pavement wear. As the recommended inflation pressures for these tyres are higher for the same loads, the level of over-inflation is likely to be less.

- Increasing the thickness (or modulus) of the upper pavement layers reduces the impact of tyre-contact patch size and pressure distribution on the subgrade compressive strains. Thus the effects described will be less for thicker, stronger pavements, and greater for thinner, weaker pavements.

- The analysis of pavement wear is based on the premise that the compressive strain in the subgrade layer is the key to pavement performance. If, however, there is a contribution to pavement wear from permanent deformations of the basecourse layer, the effects of contact patch size and pressure distribution are far more significant. The effect of using small diameter tyres, rather than correctly inflated standard tyres, on the peak compressive strain at the top of the basecourse is an increase in strain of around 76%.

7. Conclusion

The use of correctly inflated small diameter tyres would be expected to generate an increase in pavement wear when compared to correctly inflated standard tyres. The scale of this additional wear is of the same order of magnitude as that generated by over-inflating standard tyres to the levels that are common in practice.

8. Recommendations

For future research, the extent to which operators over-inflate tyres and their rationale for doing so would be worth investigating. The practice appears to have no real benefits to them and it has a negative effect on the pavement infrastructure.

An appropriate education programme aimed at encouraging operators to use correct inflation pressures could result in substantial savings in pavement wear costs without any additional expenditure.

Abstract

Small diameter tyres are increasingly being used in heavy vehicle applications. While they give operational advantages in some situations they may have a negative impact on pavement wear. This study, carried out between 1996 and 1997, investigated the implications for pavement wear of using small diameter tyres in place of standard sizes.

Two aspects of small diameter tyres are investigated. The first is how the use of small diameter tyres influences the vehicle – pavement interface in terms of tyre-contact patch size and pressure distribution. The second relates to vehicle dynamics. Small diameter tyres have lower mass and higher stiffness, which alter the vehicle dynamics and consequently the dynamic wheel forces. The implications for pavement wear of these changes are assessed.

For a typical New Zealand pavement, the tyre-contact effects of small diameter tyres results in an increase in subgrade strains of about 5% over a correctly inflated standard tyre. This corresponds to a 21% increase in pavement wear. However, the common practice is to use higher inflation pressures than required for standard size tyres which causes an increase in subgrade strains and pavement wear. The increase is similar to that generated by correctly inflated small diameter tyres.

1. Introduction

1.1 Rationale

Small diameter tyres (R19.5s and R17.5s) have increasingly been used in heavy trailer applications to help solve problems in accommodating particular types of loads. Specifically, the use of small diameter tyres reduces the load height of the vehicle allowing greater load volumes to be carried within legal height restrictions. As well, the weight of the axle assemblies, and consequently the vehicle tare weight, are reduced and thus they allow higher payloads to be carried within a gross vehicle mass limit.

The implications for pavement wear of using small diameter tyres have not previously been assessed. The impetus for this investigation arises from the increasing use of these tyres on over-dimension special permit vehicles where Transit New Zealand has discretionary control. However, the study is not limited to these classes of vehicles and the findings apply to the use of these tyres in all heavy vehicle applications.

1.2 Methodology

The use of small diameter tyres is expected to impact on pavement wear by two possible mechanisms, both of which are investigated in this study carried out between 1996 and 1997. The first is that smaller diameter tyres will have a different tyre-contact patch and will generate a different contact stress distribution. This, in turn, may influence pavement wear.

The second mechanism relates to vehicle dynamics. Small diameter tyres result in a lower unsprung mass for the vehicle. These tyres also require higher inflation pressures, which probably result in higher tyre stiffness values. These two factors will influence the vertical dynamics of the vehicle and the resulting dynamic wheel forces, which in turn will impact on pavement wear.

The first stage of the project was to undertake a literature review that focussed on previous work in this area and on related studies. The results of this review are presented in chapter 2.

The second stage was to investigate the impact of small diameter tyres on the contact pressure distributions. This part of the study was based on published information with simple regression techniques being used to estimate the implications for small diameter tyres. Chapter 3 describes this work in detail.

The third stage, which is covered in chapter 4, looked at the implications on vehicle dynamics. This was done using quarter-car computer simulation models, which were originally developed to represent the loading vehicles at the Canterbury Accelerated

Pavement Testing Indoor Facility (CAPTIF), Christchurch, New Zealand. These models are geometrically quite simple but include non-linear spring and damper elements.

In chapter 5, the results of these two aspects are combined and the pavement wear implications are assessed, with particular reference to New Zealand pavement design practice. Chapter 6 summarises the findings and presents the conclusions.

2. Literature Review

2.1 Introduction

A comprehensive search was undertaken utilising the ARRB (Australian Road Research Board) Transport Research Ltd facilities, the TeLIS facility at Works Consultancy Services, Wellington, and Industrial Research Limited's (IRL) information services. The most relevant literature is listed in the references to this report. Although a substantial number of publications relating to tyre effects and pavement wear were identified and obtained, the only research specifically addressing the effects of tyre diameter on pavement wear was the NCHRP study by Gillespie et al. (1993), which is also reported in Cebon (1993). This study gives some consideration to the effect of low profile tyres, which were of smaller diameter than the standard tyres.

A similar issue, which has received considerable research attention, is the effect on pavement wear of using wide-base single tyres instead of dual tyres. In one of the papers on this topic, Cole & Cebon (1996) identify precisely the same methodology that has been used in this study and which is outlined in chapter 2 of this report. It is to consider the effect on tyre contact-patch size and pressure distribution, the effect on vehicle dynamics through changes in unsprung mass and stiffness, and the influence of both these factors on pavement wear.

2.2 The NCHRP Study

The only research work which appears to specifically address the question of smaller diameter tyres is the NCHRP study (Gillespie et al. 1993). This work was a very large multi-factorial investigation using computer simulation models. Two generic pavement types were modelled, rigid and flexible, each at three levels of roughness. From these simulated road profiles, the loads generated by 29 different vehicle models were calculated. These loads were then applied to either 19 rigid or 13 flexible pavement designs, depending on which profiles were used. From this the resulting pavement strains were calculated and used to calculate the corresponding pavement wear.

The use of small diameter tyres (referred to as "low profile tyres") was a very minor issue in their study. Only one truck configuration of the 29 simulated used these small tyres. It appears from their report that these tyres were assumed to have the same stiffness and mass as conventional tyres, and the only difference was a higher inflation pressure. This resulted in a smaller contact patch and a higher contact pressure.

The three wear mechanisms they considered were:

- rigid pavement fatigue,
- flexible pavement fatigue, and
- flexible pavement rutting.

Rigid pavements are not used to any extent in New Zealand and, in any case, the effect of small diameter tyres on rigid pavement fatigue was found to be very small. Flexible pavement fatigue relates to cracking of the asphaltic concrete surface layer of the pavement. This was assumed to be proportional to the fourth power of the bending strains at the bottom of the asphalt layer.

For the same axle load, low profile tyres were found to generate 25% greater strains than standard tyres in the thinnest pavement, which was 2 inches (51 mm) thick. These relative strain levels reduced with increasing pavement thickness to where they were only 7% higher for a pavement thickness of 6.5 inches (165 mm). In determining equivalency factors, Gillespie et al. used the rated load for the tyres. Thus the equivalency factor for low profile tyres is calculated for an axle loaded to 17,000lb (7727 kg) which is related to a standard axle with standard tyres carrying 18,000lb (8182 kg). On this basis the equivalency factors range from 1.95 for the thinnest pavement down to 1.04 for the thickest pavement. If, instead, identical loading were used for both axles these equivalency factors would range from 2.45 to 1.31.

The rutting wear mechanism, which is considered in the NCHRP study, is through plastic deformation of the asphalt rather than any compaction or compression of the materials. On this basis an axle with small diameter low profile tyres loaded to 17,000lb was found to generate much the same level of rutting as an axle with conventional tyres loaded to 18,000lb. This approach to modelling rutting damage is based on a linear visco-elastic model of pavement material behaviour, and essentially states that the relationship is a power law with an exponent of one.

The applicability of these two flexible pavement wear mechanisms to New Zealand's unbound chipseal pavement structures is arguable. The model used in New Zealand for thin-surfaced unbound granular structures assumes that the surface layers do not contribute to the structural capacity of the pavement, and thus fatigue of the surface layer is not considered. The primary mode of structural failure is expected to be permanent deformation of the subgrade. This rutting mechanism is not the same as that in the NCHRP study.

2.3 Tyre Characteristics

The two major aspects of tyre behaviour that need to be considered are:

- contact patch size and pressure distribution, which determine the pattern of loading applied to the pavement and consequently the pavement strains;
- tyre stiffness and dynamic response, which influence the dynamic behaviour of the vehicle.

Dynamic behaviour is also influenced by the mass of the tyre, which is part of the unsprung mass of the vehicle.

A substantial body of research on tyre behaviour and modelling exists. Much of this relates to longitudinal and lateral forces, which are critical to modelling the vehicle dynamics related to handling and stability but are less important in considering pavement wear. The key issues for this study are tyre stiffness and damping which affects the vehicle dynamics and the contact pressure distribution, which generates the pavement strains and ultimately the pavement wear.

Hooker (1980) developed models for the vertical stiffness and damping of tyres. His validation is based on tests conducted on passenger car tyres. The formulation for bias ply tyres involved three spring elements and one damper element where one of the spring elements is linearly dependent on the tyre inflation pressure.

However, the formulation for radial ply tyres is very much simpler using a single spring element with stiffness proportional to inflation pressure. This implies that, for radial ply tyres, the casing stiffness and the damping are negligibly small (MacAdam et al. 1980). Measurements by Tielking (1995) show a slight non-linearity in the force – displacement relationships. However, in the normal operating range of dynamic loads, the assumption of linear behaviour appears to be adequate.

From these results it would appear that a relatively simple model of tyre stiffness could be used for determining the changes in vehicle dynamics attributable to the use of small diameter tyres. Provided we can obtain tyre stiffness data from the tyre manufacturers or their agents, these data would be relatively straightforward to incorporate in a vehicle dynamics model with reasonable confidence. In general terms, as small diameter tyres are generally also low profile, their sidewall stiffness would be expected to contribute more to their overall stiffness, which would therefore be greater than an equivalent larger tyre. As well, the operating pressure will normally be higher which also would result in increased stiffness.

The issue of contact patch size and pressure distribution is more complex. The simplest models (Gillespie et al. 1993) that are widely used for applying loads in pavement models assume a circular contact patch, and a uniform contact pressure distribution, with the pressure equal to the tyre inflation pressure. This is clearly a significant simplification. A number of researchers (Clark 1971; de Beer 1996; Marshek et al. 1985, 1986; Seitz & Hussmann 1971; Yap 1988) have investigated contact patch area and pressure distributions. Although there are some minor differences in their findings, the general pattern of results is the same.

Contact patch area and shape depend primarily on the inflation pressure and load. A tyre that is at the correct inflation pressure for its load has a contact patch that typically appears rectangular with rounded corners. The longitudinal edges of this rectangle are relatively straight while the transverse edges are more curved and are usually convex. As the inflation pressure increases (or the load decreases), the contact patch area decreases and its shape becomes more circular. Conversely, as the inflation pressure decreases or the load increases, the contact patch area increases primarily by increasing its length. The tread belt limits the possibility of a width increase. The convex transverse edges of the contact patch become less curved and can become concave.

The contact pressure distributions within the contact patch have also been measured in a number of studies (de Beer 1996; Marshek et al. 1985; Yap 1988). Again, although not identical, the results are all reasonably consistent. In the longitudinal direction the pressure distribution is remarkably uniform. It might be expected that there would be increases in contact pressure at the leading and trailing edges due to bending of the tread band, and that this effect would be different for small diameter tyres, which have greater curvatures. However, this effect is barely discernible. For lower inflation pressures and/or higher loads (the two are relative to each other), this expected edge effect may occur on sections near the centre of the tyre, but in any case its magnitude is very small.

The transverse pressure distributions are much more variable because inflation pressure and load significantly affect them. In general, with higher loads or lower inflation pressures, the contact pressures are higher at the edges because of sidewall effects and lower near the centre of the tyre. As the inflation pressure increases relative to the load, the contact pressure in the centre of the tyre increases. The measurements by Yap (1988) indicate that, with the correct match of inflation pressure and load, the contact pressure is at its most uniform. However, all three authors report peak contact pressures that are more than double the inflation pressure for some test configurations.

From data supplied by tyre manufacturers, the recommended inflation pressures for standard tyres at New Zealand axle loads are lower than the values commonly used by operators. A number of possible reasons exist for this. Over-inflation generates increased tyre wear but this increase is much less than the increase caused by a similar level of under-inflation. Thus it is safer to err on the high side. Over-inflation reduces rolling resistance and hence may improve fuel economy but at the expense of a deterioration in ride quality. Optimum inflation pressure is load-dependent. However, without any easy method for rapid alteration of inflation pressure, setting the pressure for the maximum load is simpler. Similarly, if the inflation pressures are not checked and adjusted as frequently as desirable, particularly with dual tyre sets, over-inflation reduces the risk of being under-inflated between checks.

Small diameter tyres have higher recommended inflation pressures for the same load and may be less likely to be over-inflated to the same extent.

2.4 Road Wear

The principal road wear issues have been discussed in chapter 2.2 of this report, on the NCHRP study. The fundamental question for any vehicle – road interaction analysis in the New Zealand context is to what extent can results of overseas studies on flexible pavement be applied to the thin-surfaced unbound structures that predominate in New Zealand. Work was undertaken (Pidwerbesky 1992, de Pont et al. 1999a) at the Canterbury Accelerated Pavement Testing Indoor Facility (CAPTIF), Christchurch, New Zealand, to investigate this issue. Fatigue-induced cracking of the asphalt layer is a damage mechanism for asphaltic concrete (AC) pavement which does not apply to thin-surfaced structures. For both AC pavements and thin-surfaced pavements, the CAPTIF tests found that most of the rutting occurred in the basecourse layer, rather than in the subgrade. The design models are based on the assumption that rutting will occur in the subgrade.

The conversion from applied stress in the form of contact pressure to pavement strains, and subsequently to pavement wear, is still a matter of debate. Even for AC pavements for which a substantial research database exists, there is still a diversity of opinion. Gillespie et al. (1993), for example, suggested that rutting damage is directly proportional to the applied load, i.e. an exponent of unity, while Pidwerbesky (1989), in summarising design practice around the world, quotes exponents for rutting ranging from 3.3 to 8. As there is no definitive answer to this question, the impact of a range of values is evaluated in this study, and used to put upper and lower bounds on the impacts.

3. The Tyre – Road Interface

3.1 Introduction

The issue of how changing to smaller diameter tyres influences the tyre-contact patch and the contact pressure distribution is investigated. The approach is based on interpreting existing data and published results as it was beyond the scope of this study to undertake any new experimental work.

From the literature survey presented in chapter 2 of this report, no research specifically addressing issues related to small diameter tyres has been identified. This is not surprising as only a small number of studies have investigated contact patch and pressure distributions and these have focussed on the tyre sizes that are most commonly used.

3.2 Tyre Specifications and Data

Firestone in Auckland, and South Pacific Tyres in Upper Hutt were approached with a request for information. Specifically we asked for comparative data between standard sized tyres and the small diameter alternatives relating to:

- contact patch - both area and shape at recommended inflation pressures and, if possible, some indication of how these change with inflation pressure;
- contact patch pressure distribution;
- tyre stiffness - as a function of displacement if non-linear, and as a function of inflation pressure;
- tyre mass;
- recommended operational characteristics such as rated speed, load limits, and inflation pressure.

Both companies were very helpful and supplied considerable data. However, neither was able to supply all the requested information, particularly in relation to the first three items listed. These three topics have been investigated by a number of researchers and thus we have used their findings to assess the impact of these factors.

TERNZ has a substantial database of tyre properties for use in vehicle simulation models. Some of these data come from the tyre manufacturers and some from measurements conducted at the University of Michigan Transport Research Institute (UMTRI). Although much of these data relate primarily to vehicle stability modelling, some values are for vertical tyre stiffness which are relevant to this study. UMTRI have also published a heavy vehicle "factbook" (Fancher et al. 1986) which contains the range of values of various characteristics including tyre stiffness taken from their measurements. Further data were obtained from a tyre-testing program conducted at the Goodyear Tyre Company as part of a US Federal Highways Administration (FHWA) project (Sebaaly 1992) on dynamic forces on pavements.

3.3 Tyre Footprints and Contact Pressures

It is important when reviewing these data to distinguish between gross and net contact areas. The gross contact area is the whole area enclosed by the outer boundary of the contact patch, whereas the net contact area excludes the areas within this boundary which do not contact the pavement. The range of values for the ratio of net to gross contact area for the data obtained was 0.67 to 0.8. The data from South Pacific Tyres, which give gross and net pressures rather than areas, cover a range of tyre sizes mostly at a single combination of inflation pressure and load, though for a few tyre sizes two inflation pressure/load combinations are given. These data give no indications of any correlation between tyre size and the ratio of net to gross contact area. Where data for two different loading configurations on the same tyre are given, the differences in the ratio of net to gross area are small and there is no obvious pattern to them.

The FHWA data cover a smaller selection of tyres over a wider range of loads and pressures. In general, increasing tyre loads results in an increase in the ratio of net to gross contact area though the effect is quite small. Increasing tyre pressure at a given load tends to decrease the ratio, but the effect is very small and does not occur in all cases.

The net average contact pressure increases with inflation pressure but at a slower rate. For the standard 11R22.5 tyres, at the recommended inflation pressure for the load, the two are of similar magnitude. This fits with measurements of contact pressure distribution, which is at its most uniform when the tyre is at its recommended inflation pressure.

Considering then a single axle fitted with dual tyres loaded to the legal limit of 8.2 tonnes. Each tyre is loaded to 2050 kg. For 11R22.5 tyres, which is the typical standard full size, the recommended inflation pressure is approximately 535 kPa (77 psi). Assuming that the net average contact pressure is the same, the net contact patch area would be 0.0376 m^2. In a tandem or tridem axle configuration, the maximum axle loads are less (7.5 tonnes and 6 tonnes respectively). At these wheel loads (1875 kg and 1500 kg), the required inflation pressures are lower (approximately 475 kPa and 350 kPa)*. At these pressures the corresponding net contact areas are 0.0387 m^2 and 0.042 m^2.

Multi-linear regression on the data from the FHWA project gives a good fit for net average contact pressure as a function of load and inflation pressure ($r^2 = 0.99$). The resulting coefficients are given in Table 3.1.

Table 3.1 Regression coefficients for net average contact pressure for full size tyres.

Tyre size	Constant coeff.	Tyre load coeff.	Inflation pressure coeff.
11R22.5	193	0.059	0.52
295/75R22.5	195	0.041	0.55
425/65R22.5	186	0.031	0.60

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* These values are determined by extrapolation.

This gives an alternative (and probably more accurate) method for determining net average contact pressures and areas. The three load cases considered above give calculated net average pressures of 592, 551 and 464 kPa with net average contact areas of 0.0340, 0.0334 and 0.0317 m^2.

In practice, higher inflation pressures tend to be used, 690 kPa (100 psi) being typical, regardless of load. Using these coefficients, the calculated net average contact pressures are 670, 660 and 638 kPa with corresponding net contact areas of 0.0300, 0.0279 and 0.0231 for the three load cases (2050, 1875 and 1500 kg), respectively.

The wide range of tyres available complicates the issue of the effect of using small diameter tyres. Many of these (particularly the smaller sizes) are not rated to carry the higher of the three load cases outlined. Furthermore, the data on net average contact pressures and areas are much more limited and insufficient for regression fitting. The two most widely available series of smaller diameter tyres available are the R19.5 and R17.5. The R17.5 tyres will be considered as being the more extreme case. On the standard 15° drop centre rims, no R17.5 tyre has a rated axle load capacity of 8200 kg in a dual tyre configuration. 10R17.5 tyres are rated at 8000 kg and 235/75R17.5 tyres are rated at 7200 kg. However, by using tapered or flat-base rims, the rated load capacity of both these tyre sizes (and some of the narrower ones) can be increased to exceed the required 8200 kg. Of these two, the low profile tyre (235/75R17.5) represents the biggest change from the standard size and is likely to have the greatest impact.

From the tyre manufacturer data sheets, the inflation pressures required on this tyre for the three load cases (2050, 1875, 1500 kg) are 825, 738 and 560 kPa. The only figure available for net average contact pressure is 872 kPa, which was measured at an inflation pressure of 725 kPa and a tyre load of 1900 kg. The data are insufficient to repeat the regression analyses, that were undertaken for full size tyres. However, for three of the R19.5 tyres and one of the R17.5 tyres, there are data at two combinations of inflation pressure and wheel load, reflecting the load limit for different rim types. These data are shown in Table 3.2.

Table 3.2 Data for smaller diameter tyres.

Tyre size	Tyre Load (kg)	Inflation pressure	Net average contact pressure
215/70R17.5	1600	600	766
215/70R17.5	2180	850	964
245/70R19.5	2060	725	844
245/70R19.5	2500	850	958
265/70R19.5	2240	725	815
265/70R19.5	2725	850	933
285/70R19.5	2500	725	796
285/70R19.5	2800	825	897

By taking the difference of the data for each tyre size, the constant term can be eliminated from the multi-linear fit used previously. If we assume that the other two coefficients do not depend significantly on the tyre size, regression analysis is undertaken to calculate these coefficients. These are 0.106 for the tyre load coefficient, and 0.558 for the inflation pressure coefficient, with an r^2 value of 0.97 which indicates a good fit. From these values estimates of the constants for each of the tyre sizes can be back-calculated. The resulting coefficients are given in Table 3.3.

Although the assumptions made in deriving these coefficients are somewhat crude, the values are reasonably credible when compared with the values in Table 3.1 which have a stronger experimental backing. If the two calculated coefficients are used for the tyre under consideration, the 235/75R17.5, a constant coefficient value of 266 is required in order to match the measured data. Using these three coefficients, net average pressures and net average contact patches can be calculated for the three load cases. The three pressures are 944, 877 and 737 kPa with corresponding contact patches of 0.0213, 0.0210 and 0.0200 m^2. The results for the different tyre configurations and loads are summarised in Table 3.4.

Table 3.3 Regression coefficients for net average contact pressure for small diameter tyres.

Tyre size	Constant coeff.	Tyre load coeff.	Inflation pressure coeff.
215/70R17.5	261	0.106	0.558
245/70R19.5	221	0.106	0.558
265/70R19.5	172	0.106	0.558
285/70R19.5	134	0.106	0.558

Table 3.4 Net contact patch areas and pressures for different tyres and loads.

Tyre load (kg)	11R22.5 at recommended inflation		11R22.5 at 690 kPa inflation		235/7517.5 at recommended inflation	
	Contact patch area (m^2)	Contact pressure (kPa)	Contact patch area (m^2)	Contact pressure (kPa)	Contact patch area (m^2)	Contact pressure (kPa)
1500	0.0317	464	0.0231	638	0.0200	737
1875	0.0334	551	0.0279	660	0.0210	877
2050	0.0340	592	0.0300	670	0.0213	944

These net average contact pressures of the R17.5 tyres are approximately 55 to 60% higher than those of the standard 11R22.5 tyre with the same loads and at the recommended inflation pressure. If it is assumed that the standard tyre is inflated to 690 kPa regardless of load, then these net average contact pressures are only 13 to 40% higher with the smallest difference occurring at the lowest of the wheel loads. The net contact areas are inversely proportional to these pressures.

3.4 Non-uniform Pressure Distributions

A number of researchers have undertaken measurements of contact pressure distributions. For obvious reasons they have focussed on the most commonly used tyre sizes. There are comparative measurements of radial ply and bias ply tyres and of standard and wide-base single tyres, but not of smaller diameter tyres.

The issue of contact pressure distribution can be divided into two aspects, the longitudinal distribution and the transverse distribution. Of these the longitudinal distribution might be expected to be more influenced by tyre diameter. At the leading and trailing edges of the contact patch, the tyre tread is subjected to significant bending and for a smaller diameter tyre this bending is greater. However, the measurements of longitudinal pressure distribution, as shown by the example in Figure 3.1 (from Yap 1988), show no significant edge effects. In fact, the distribution is remarkably uniform. Thus tyre diameter is not expected to have any significant impact on the longitudinal pressure distribution.

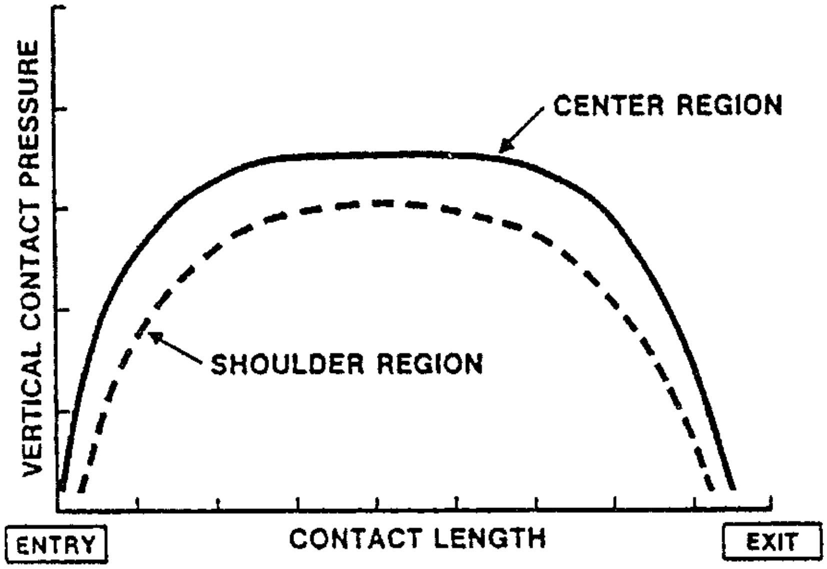

Figure 3.1 Longitudinal pressure distribution (from Yap 1988).

Examples of the transverse pressure distributions from the same author are given in Figures 3.2 and 3.3. Both these figures relate to a constant load and varying inflation pressures. The same paper also contains plots of constant inflation pressures and varying loads. These have identically shaped pressure distributions to the above figures but with differences in the absolute vertical position.

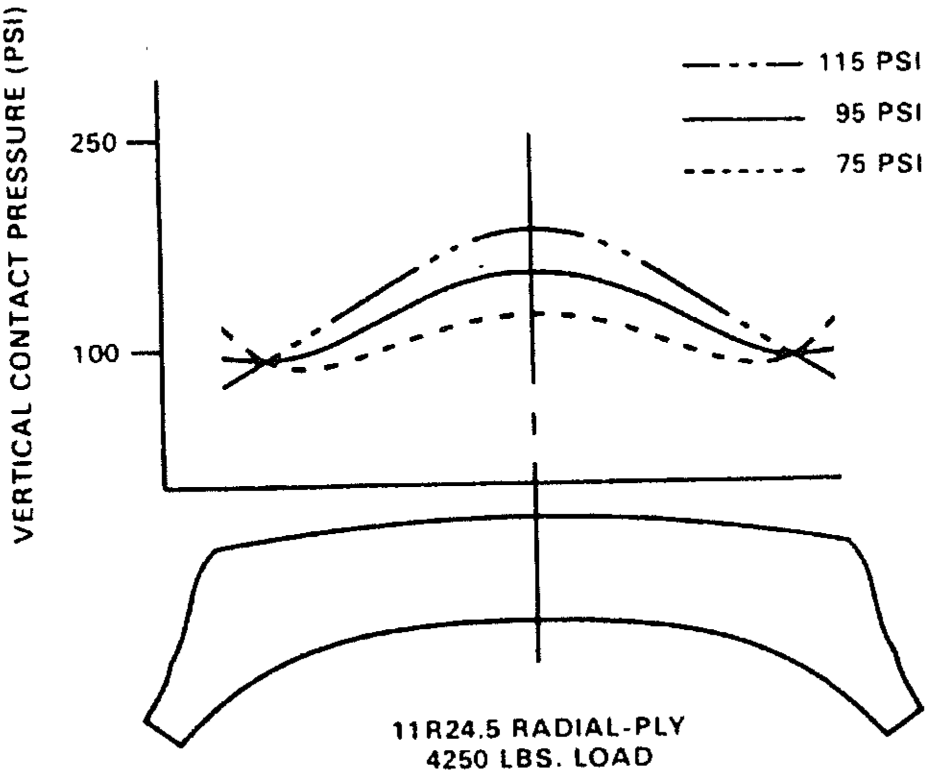

Figure 3.2 Transverse pressure distributions for a 11R24.5 tyre (from Yap 1988).

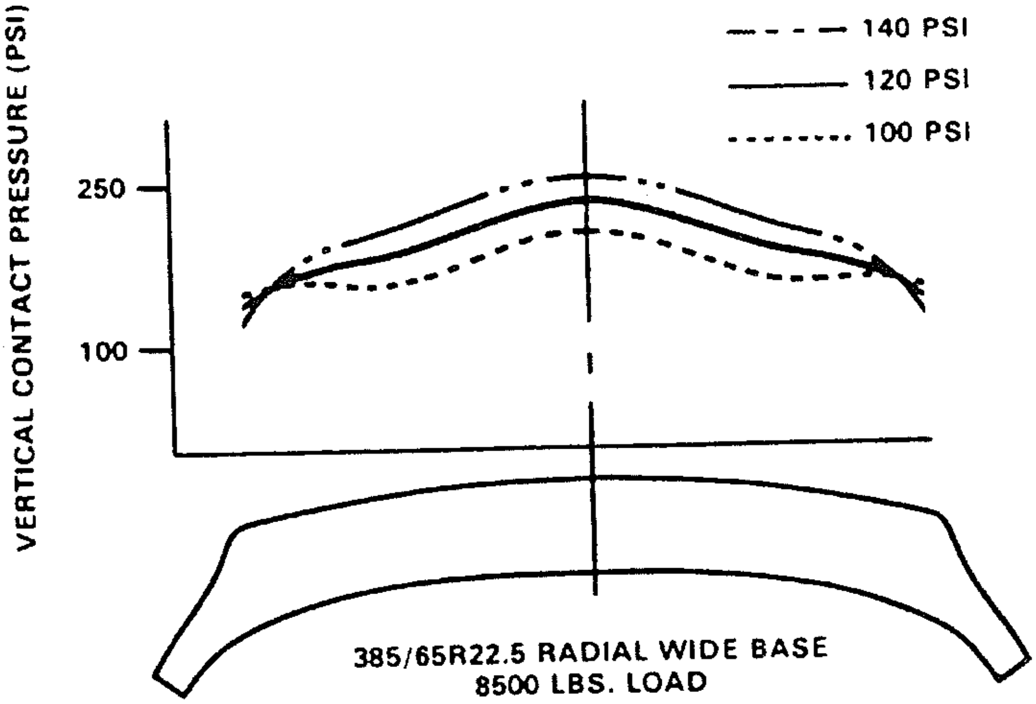

Figure 3.3 Transverse pressure distributions for a wide-base tyre (from Yap 1988).

Although there are subtle differences in the shapes between these two tyre types, the overall distributions are very similar, and there is no reason to believe that a small diameter tyre would not behave in the same way. Data from various reports indicate that, across a range of loads and inflation pressures, the peak contact pressure values are between 55% and 100% higher than the net average contact pressure. The peak contact pressures are also 55% to 100% higher than the inflation pressures. Clearly as, in general, the net average contact pressure does not equal the inflation pressure, these two maxima do not occur at the same values of inflation pressure and wheel load. For the three tyres in the FHWA data set (Sebaaly 1992) there are no clear relationships. The ratio of peak contact pressure to inflation pressure decreases with increasing inflation pressure for all load cases on each tyre. Also, the influence of wheel load on this ratio is less clear cut as are the differences between tyres.

It seems reasonable to assume that, as an upper bound, the peak contact pressure will be as high as double the inflation pressure. At higher inflation pressures it may well be lower than this (1.55 to 1.7 times is typical for the FHWA tyres), but there is no way of assessing this value with any confidence.

3.5 Summary

Tyre data were obtained from suppliers, from TERNZ's database, and from research publications. From these data the net average contact pressures and areas have been estimated for standard size and small diameter tyres.

Compared with the standard size tyre, a small diameter tyre will generate net average contact pressures that are 55-60% higher for the same load where both tyres are inflated to the recommended inflation pressure for the load. Correspondingly the net average contact areas are 55-60% lower. In practice, standard tyres are commonly operated at inflation pressures that are higher than recommended for the load. As explained in chapter 2.3 of this report, there are a number of possible reasons for this. The increases in net average contact pressure from using a correctly inflated small diameter tyre, rather than a "standard" tyre inflated to 690 kPa (a typical value), are much less, particularly at lower loads.

The final issue to be addressed at this stage is to evaluate the extent to which an assumption of uniform pressure distribution is false, and whether any size or pressure related factors exist. From the published research, the maximum contact pressure was found to be up to double the inflation pressure. There is no clear evidence that this is related to tyre size, and the ratio appears to decrease with increasing inflation pressure but this effect is difficult to quantify.

The over-riding consideration in terms of this study is what impact, if any, these higher contact pressures have on pavement wear in the New Zealand context.

4. Vehicle Dynamics Effects

4.1 Introduction

In this chapter the implications of small diameter tyres on dynamic wheel forces are assessed. Basically two aspects of small diameter tyres influence vehicle dynamics. First, small diameter wheels and tyres have a lower mass leading to a significantly lower unsprung mass for the vehicle. Second, there may be differences in tyre stiffness, which will also affect dynamic behaviour.

To assess the significance of these factors a quarter-car vehicle simulation model was used. This is a simplification of the real situation as the body resonance is limited to one mode, "bounce", rather than three, "bounce", "pitch" and "roll". Similarly, the axle modes are simplified to a single axle hop mode.

However, in the context of a comparative analysis this simplification has advantages over a whole vehicle model. With a whole vehicle model the various resonance modes of the sprung and unsprung mass interact with each other in a complex manner to generate the overall dynamic response. Modifying a single parameter such as tyre stiffness can alter this interaction between the resonance modes. With the simple quarter truck model, no wheelbase or axle interaction effects complicate the results and there is less concern that the results are specific to the particular vehicle configuration modelled. This approach was taken by Cole & Cebon (1996) in a study comparing wide-single and dual tyres.

Two suspension types were modelled based on the two suspensions used at the CAPTIF facility during the OECD DIVINE test (de Pont et al. 1999b). In terms of "road-friendliness", these two suspensions represent opposite ends of the spectrum. As the suspensions modelled are non-linear, their response is dependent on the amplitude of the excitation. That is, they will respond differently to different levels of road roughness, and it is not simply a matter of scaling. To take this into account three profiles of different roughness were used for the simulations.

4.2 Calibrating the Vehicle Simulation Models

Quarter-car simulation models have been built which have been validated using measured data from the CAPTIF vehicles. For these investigations two basic model configurations were used, one with an air-spring suspension with viscous damping, and the other with a steel leaf-spring suspension. Both models were run with both small diameter and standard sized tyres.

The purpose of this analysis is to compare the performance of small diameter tyres with that of standard tyres. For this comparison, while choosing vehicle parameters that are credible is important, it is not necessary to replicate the dynamic behaviour of any particular vehicle. The vehicle parameters listed in Table 4.1 were used for the analyses.

The static wheel load chosen was based on the legal axle load for a tandem axle configuration. It is assumed that small diameter tyres are used primarily on trailers and that, in general, would be used in axle groups rather than on single axles. It is then rather arbitrary whether to use the axle load values for a tandem or a tridem.

The unsprung mass values come from data supplied by Steel Bros (NZ) Ltd for specific axle sets used by that company for the trailers they manufacture. These values are assumed to be typical.

The stiffness of the air spring and damping rates for the shock absorber come from measured data for the CAPTIF vehicle suspension. The spring in this model is linear while the damper is non-linear, to the extent that the linear damping rate depends on whether the shock absorber is compressing or extending.

Table 4.1 Parameters used for simulation models.

Parameter	Unit
Total static wheel load	3750 kg
Unsprung mass (11R22.5 tyres)	364 kg
Unsprung mass (235/75R17.5 tyres)	262 kg
Air-spring stiffness	304 kN/m
Shock absorber bump damping rate	8.64 kN/m/s
Shock absorber rebound damping rate	27.27 kN/m/s
Steel leaf-spring compression envelope stiffness	~1234 kN/m
Steel leaf-spring extension envelope stiffness	~1169 kN/m
Beta parameter – compression	0.001143 m
Beta parameter – extension	0.0127 m
Tyre stiffness (11R22.5 at 690 kPa)	837 kN/m
Tyre stiffness (11R22.5 at 485 kPa)	680 kN/m
Tyre stiffness (235/75R17.5 at 740 kPa) est. max.	950 kN/m

The steel leaf-spring suspension is modelled using the method developed by Fancher et al. (1980) at the University of Michigan Transportation Research Institute (UMTRI). The model parameters used were supplied by C.B. Winkler (pers.comm., UMTRI spring model, 1992) as example data from measurements. The stiffness values for the compression and extension envelopes were given as look-up tables and were used in this form. The values in Table 4.1 are the average stiffnesses for these steel leaf springs as calculated by linear regression, and are therefore shown as approximate. The data as supplied generated relatively low levels of damping and so a second set of runs was done where the separation between the compression and extension envelopes was increased to obtain damping values closer to those measured at CAPTIF.

The stiffness values for the 11R22.5 tyres are derived from data presented by Sebaaly (1992) in a study undertaken for the FHWA. He measured load-deflection curves for three tyre types at a range of tyre inflation pressures. These load-deflection curves are reasonably linear and so, for a given inflation pressure, it was possible to derive a tyre stiffness value by linear regression. The relationship between these tyre stiffness values and inflation pressures is also approximately linear. For the baseline models using full size tyres, an inflation pressure of 690 kPa (100 psi) was used. As discussed in chapter 2 of this report, this inflation pressure is significantly higher than needed for the wheel loads and so a lower inflation pressure of 485 kPa was also considered.

For the small diameter tyres, the question of tyre stiffness was more difficult as no specific data were found. Sebaaly also presents data for low profile 295/75R22.5 tyres, which indicate a slight stiffness increase (5% or so) particularly at higher inflation pressures. Gillespie et al. (1993) considered small diameter tyres in their simulation models but used the same stiffness values as for normal size tyres. Small diameter tyres need to operate at higher inflation pressures. The results in chapter 3 of this report indicate that, for an axle load of 7500 kg, an inflation pressure of 738 kPa is required. Sebaaly's data for 295/75R22.5 tyres indicate a tyre stiffness of 920 kPa at this inflation pressure. Assuming that reducing tyre size could further increase the tyre stiffness, a value of 950 kPa was chosen.

The two models (air and steel suspension) with normal size tyres were subjected to the EC bump test (Council of European Communities 1992) (which involves running the vehicle up a ramp and over an 80 mm drop at crawl speed), and the suspension deflection response was calculated. The air-sprung vehicle bounce mode, which was excited, had a natural frequency of 1.39 Hz and a damping ratio of 23%. These values represent a well performing and "road-friendly" suspension. The steel-sprung vehicle had a natural frequency of about 2.6 Hz and a damping ratio of 4% to 6%, depending on which displacement peaks were used to calculate it. By increasing the separation between the compression and extension envelopes to match the measured behaviour at CAPTIF, a damping ratio between 13% and 22% was obtained.

In general, the level of damping depends on the amplitude of the suspension motion. Lower values occur with the larger amplitude of the initial motion and higher values for the subsequent lower amplitude bounces. Under both damping levels, this suspension would be regarded as relatively aggressive towards pavements.

4.3 The Three Pseudo-Road Profiles

The road profile was generated randomly from a designed power spectral density function (PSD). In line with the ISO 8608 standard (1995) on road profile data, the PSD was designed to be proportional to the inverse of the wavenumber squared. That is, the waviness value was chosen to be –2. A relatively long section of just over 1500 m was generated with profile points every 0.25 m. Rather than generate three completely independent profiles, the amplitudes of the elevations were scaled to generate the three profiles required. This means that they are directly comparable to each other.

The scaling was done in order to achieve suitable IRI (International Roughness Index) values. These and the other roughness measures, which were calculated, are summarised in Table 4.2 below.

Table 4.2 Roughness statistics for the three pseudo-road profiles.

Statistic	Smooth	Medium	Rough
IRI (mm/m)	1.5	3	6
NAASRA Roughness (counts/km)	43	87	176
Generalised roughness $G_d(n_0)$ (m^3)	8.5×10^{-6}	34×10^{-6}	136×10^{-6}

The IRI values were calculated from the actual profile data. The NAASRA roughness values were calculated using one of the linear relationships determined by Prem (1989). As the profile is an artificially generated one rather than a measured one, it is arguable which of the five relationships presented by Prem was most appropriate. However, they all give similar results and the differences in using one of the other forms would only be of the order of 1 - 2 counts/km.

The generalised roughness G_d (n_0) is defined in the ISO 8608 standard and is the value of the PSD at a wavenumber of $n_0 = 0.1$ cycles/m. From the road classification scheme included in the standard, these roads would be class A, B and C respectively which, as the standard goes down to H, would seem rather better than expected. However, other work on road roughness (de Pont 1997) also indicates that the ISO standard appears to rate roads rather better than when using IRI.

4.4 Results and Analysis of the Simulation Runs

All three models were run over the three profiles in four configurations. In all cases the test speed was 90 km/h (25 m/s). The four configurations were:

1. The standard configuration with 11R22.5 tyres inflated to 690 kPa.
2. 11R22.5 tyres inflated to 485 kPa with tyre stiffness adjusted accordingly.
3. Small diameter tyres with the unsprung mass adjusted accordingly but with the same tyre stiffness value as the standard configuration.
4. Small diameter tyres with the tyre stiffness increased to 950 kN/m.

From these runs the wheel forces were determined and the dynamic load coefficients (DLC) were calculated. The results are relatively straightforward to analyse. Consider first the air-sprung vehicle figures, which are shown in Table 4.3.

Table 4.3 DLC values for air-sprung vehicle simulations.

Configuration	Smooth	Medium	Rough
11R22.5 at 690 kPa	0.033	0.068	0.137
11R22.5 at 485 kPa	0.030	0.060	0.122
Small diameter tyres at stiffness = 837 kN/m	0.031	0.063	0.127
Small diameter tyres at stiffness = 950 kN/m	0.033	0.067	0.135

For standard size tyres, reducing the tyre inflation pressure to the recommended level reduces the dynamic loads by around 10% or slightly more. However, as the dynamic loads are already relatively low this is not very significant. Reducing the unsprung mass instead through the use of small diameter tyres also has a positive effect on dynamic loads but only by just over half as much. If the change to small diameter tyres is associated with an increase in tyre stiffness, which will almost certainly be the case because of higher inflation pressure, there is a negative effect on dynamic wheel loads but again this is very small. The combination of the two effects appear to cancel each other out so that the net effect of lower unsprung mass and higher tyre stiffness is virtually no change in dynamic loading.

It is worth noting that the change in the air-sprung vehicle's force response is relatively linear with increasing roughness. This is because the suspension model is only slightly non-linear.

For the steel-suspended vehicle, results for which are shown in Tables 4.4 and 4.5, the impact of these various configuration changes is generally even smaller. The exception is the case of the steel spring with low damping on a rough road.

Table 4.4 DLC values for simulations of steel leaf-spring vehicle with low damping.

Configuration	Smooth	Medium	Rough
11R22.5 at 690 kPa	0.075	0.147	0.447
11R22.5 at 485 kPa	0.073	0.144	0.388
Small diameter tyres at stiffness = 837 kN/m	0.072	0.143	0.459
Small diameter tyres at stiffness = 950 kN/m	0.073	0.146	0.418

Table 4.5 DLC values for simulations of steel leaf-spring vehicle with high damping.

Configuration	Smooth	Medium	Rough
11R22.5 at 690 kPa	0.107	0.156	0.262
11R22.5 at 485 kPa	0.105	0.152	0.251
Small diameter tyres at stiffness = 837 kN/m	0.101	0.150	0.255
Small diameter tyres at stiffness = 950 kN/m	0.103	0.152	0.259

As with the air-sprung vehicle, reducing the tyre inflation pressure reduces the dynamic wheel forces but only by the order of 2 - 3%. Reducing the unsprung mass also reduces the dynamic wheel forces though, in this case, the effect is slightly greater than the inflation pressure effect for the smooth and medium roads. Again, when the two effects of reduced unsprung mass and increased inflation pressure are combined, the net effect is very little change.

The effect of the non-linear spring model is clearly apparent in these results. The effects of the changes are amplitude-dependent and the wheel force response is not linearly related to the roughness. This is particularly so for the first series of runs (Table 4.4) where the spring has low friction damping. In this case, on the rougher roads the increase in dynamic loads is disproportionately high.

Furthermore the effects of changes in tyre stiffness and unsprung mass are larger, and not entirely consistent with those of the other runs. It is also interesting to note that reducing the friction damping on a steel leaf-spring suspension reduces the level of dynamic wheel forces on smooth roads but at the expense of higher dynamic wheel forces on rough roads.

The implication of these results is that a change to small diameter tyres would have a negligible effect on dynamic wheel forces. Thus the influence on pavement wear attributable to dynamic wheel loads is similarly negligible. Extending these results to whole vehicles is equally straightforward. The main impact of these changes is on the unsprung mass resonances of the vehicle. These will not change significantly when going from a quarter car to a whole vehicle. Thus the use of small diameter tyres is expected to cause minimal change to the level of dynamic load generated by the vehicle, and consequently to the level of pavement wear caused by that dynamic load.

5. Implications for Pavement Wear

5.1 Introduction

In the previous two chapters the impact of using small diameter tyres on the tyre-contact pressure distribution and on vehicle dynamics are assessed. However, the real issue is what effect these changes have on pavement wear, particularly for New Zealand roads.

The effect of small diameter tyres on dynamic wheel forces has been shown in this report to be negligible within the range of parameter values tested. Thus using small diameter tyres will result in no significant change in the pavement wear that is attributable to dynamic loading.

However, small diameter tyres typically operate at higher inflation pressures, and thus for the same axle loading are expected to have smaller contact patch areas. As well, the contact pressure distribution is not necessarily uniform, so the peak contact pressures may be significantly higher. Higher contact pressures will lead to higher pavement strains, which in turn will lead to more pavement damage. An alternative approach is to consider operating the small diameter tyres at lower axle loads, and to estimate the axle load that will generate the same level of damage as a legal limit axle with standard tyres. In this chapter an attempt is made to quantify these effects and also to estimate the pavement wear implications.

Most pavements in New Zealand are comprised of unbound granular flexible pavements with thin surfacing. The design model for these pavements is based on multi-layer linear elastic theory. This model assumes that thin surface layers, of thicknesses of less than 35 mm, 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. While there is some debate of the validity of this model, there is as yet no universally accepted alternative.

However, virtually all of the research studying the wear of flexible pavements conducted overseas 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 which is supposed to be the main cause of cracking in the asphalt. Therefore, 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 modulus of the former relies on the moisture content of the aggregate. Furthermore, when unbound aggregates are near or at saturation, the stresses from 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.

On the basis of this design model then, the main issue for pavement wear is the extent to which the contact patch and pressure distribution changes associated with changing to small diameter tyres impact on the vertical compressive strains in the subgrade. The pavement response models used for flexible pavements all assume a circular contact patch with a uniform contact pressure. Thus, while they could be used to look at the effect of changes to the contact patch size, they cannot be used to investigate changes in contact pressure distribution.

However, these models are based on the theory of linear elasticity and therefore the response to more complex loading conditions can be calculated using linear combinations of simpler cases. Non-uniform contact pressure distributions can be represented as the sum of a set of uniform pressure distributions with different size contact patches. The VESYS3 software from the Federal Highways Administration (FHWA) in the United States was used to investigate these effects on a typical New Zealand pavement design. VESYS3 has been extensively validated on asphaltic concrete pavements. Its applicability to thin-surfaced unbound pavements is the subject of debate because, like the pavement design model, it is based on linear-elastic layer theory. However, there is no widely accepted alternative model.

5.2 The Primary Response Model for Pavements

For this analysis a thin-surfaced unbound granular pavement design of three layers, typical for New Zealand roads, was used. The layer thicknesses and material properties used for the model are listed in Table 5.1.

Table 5.1 Pavement design parameters used in the model.

Layer	Thickness (mm)	Modulus (MPa)	Poisson Ratio
Chipseal	25.4	3000	0.33
Basecourse	254	300	0.4
Subgrade	∞	80	0.4

This choice of parameters was somewhat arbitrary but the effect of changing them will be discussed in this chapter. The modulus value used for the surface layer is the most contentious, as this value is typical for a thicker asphaltic concrete layer. As the layer thickness is reduced, and the size of the aggregate particles becomes significant relative to the layer thickness, the modulus is assumed to decrease so that the layer provides a negligible contribution to the pavement structure. As the layer stiffness is also a function of the thickness cubed, the reduction in thickness itself very significantly reduces the contribution of this layer to the pavement structure, and consequently the value used for the modulus is not that critical. For example, reducing the modulus of the chipseal layer to effectively zero increases the deflection at the top of the subgrade by 17% for all reasonable contact patch radii. Thus this would make no difference to a comparison of the relative strains for different contact patch sizes and contact pressures. The thickness values were selected to fit in easily with VESYS, which uses imperial units.

The loading was set up to calculate the response for 12 contact patch sizes with radii ranging from 12.7 mm to 152.4 mm, in 12.7 mm increments. The pavement response was calculated at four depths: 25.4 mm, 50.8 mm, 279.4 mm and 406.8 mm. In the vertical direction VESYS calculates deflections rather than strains, and so, by calculating the deflections at two depths in each of the basecourse and subgrade layers, the average vertical strains can be estimated.

The solutions for the two smallest of these contact patches appeared to be unstable in the vicinity of the centre of load application, and these results were not used in the subsequent calculations.

Figure 5.1 shows the calculated deflections at the top of the subgrade for four different contact patch sizes normalised by load. Thus, to get the actual deflection for a given tyre load, it is necessary to multiply the value by the load. For this particular pavement design, the size of the contact patch has some effect on the subgrade deflection directly under the tyre and for the first 0.2 m from the centre of the load. Beyond this distance there is no significant effect.

The deflections at the top of the subgrade, and those at 0.127 m further down the subgrade, were then used to calculate the average compressive strain in the top of the subgrade layer. The results of this calculation are shown in Figure 5.2, again normalised in the same way as those in Figure 5.1. As with the deflections, contact patch size has a visible effect on the strain values in the area close (within 0.2 m) to the point of load application. The relative magnitude of the effect is greater with strain than it is for deflections.

To make these results easier to use, the relationships between these measurements and contact patch size were investigated. For a given radial position within the range of contact patch sizes of interest, both deflections and strains were found to vary approximately linearly with the inverse of the contact patch radius.

To simplify interpolation and to minimise the computation errors, a linear regression analysis was done to obtain a relationship between peak strain and peak deflection against the inverse of the contact patch radius.

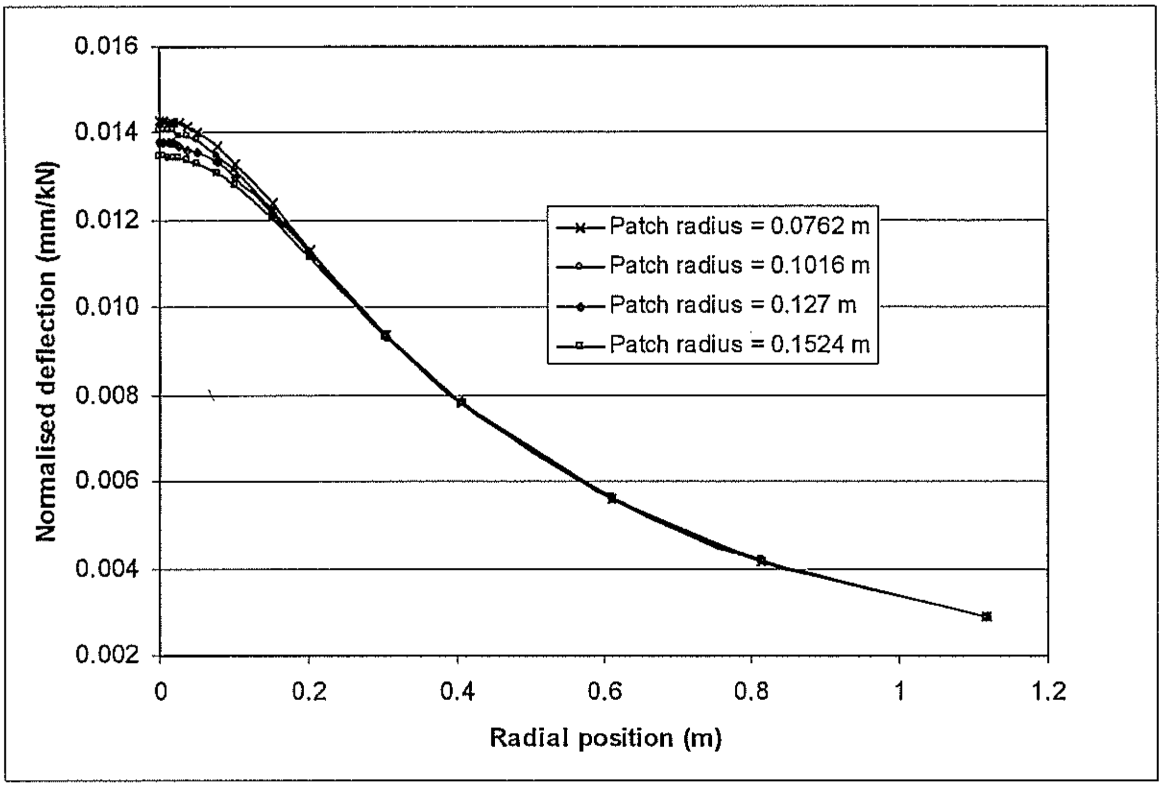

Figure 5.1 Normalised deflections at the top of the subgrade of the analysed pavement design for different contact patch sizes.

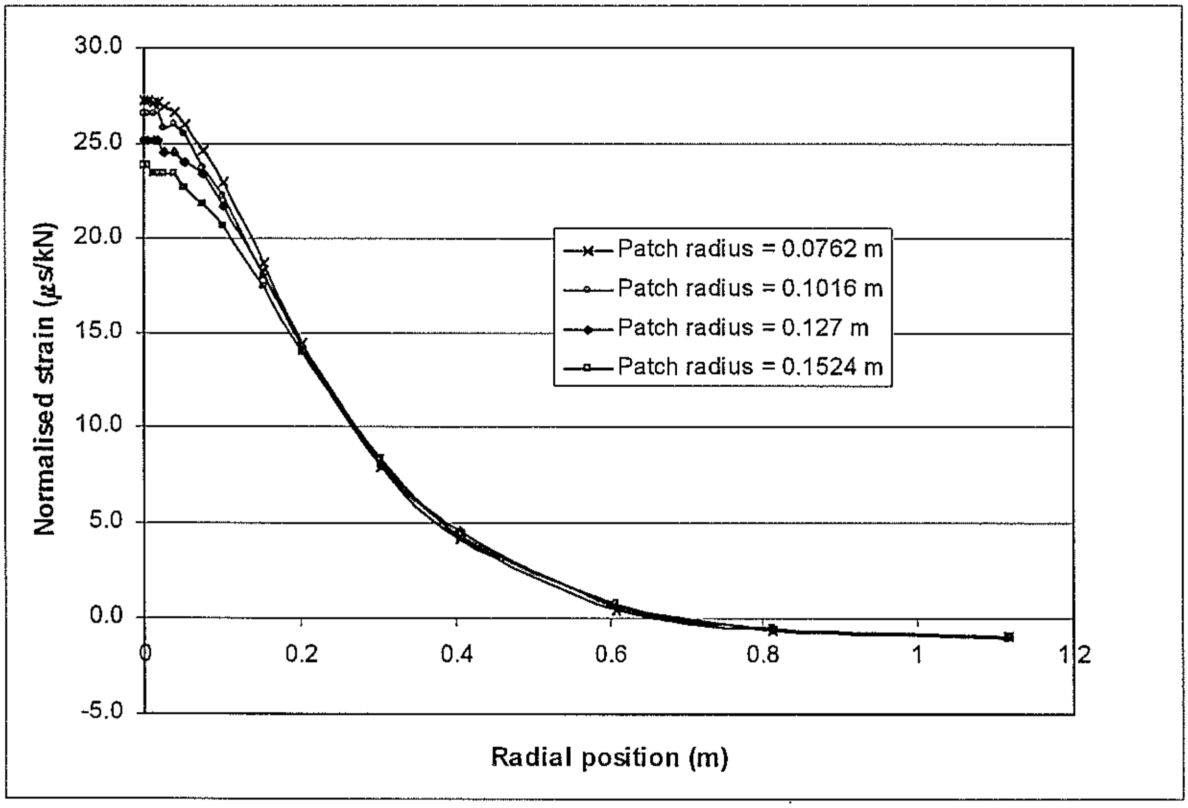

Figure 5.2 Normalised compressive strains at top of subgrade of the analysed pavement design for different contact patch sizes.

5.3 The Effect of Contact Patch Size

The issue of net versus gross contact patch area, which was discussed in chapter 3.3 of this report, arises again here. VESYS assumes a circular contact patch with a uniform pressure distribution. The most logical approach would be to use the gross contact patch and the mean gross contact pressure, as this gives the closest approximation to the boundary of the contact patch. At the surface of the pavement, the net contact pressures are important as they generate the local applied stresses. In the lower layers, local effects have been smoothed and so the gross pressure values are more relevant. As this analysis is comparative and the gross and net values are roughly proportional to each other, the choice does not really affect the results.

Consider the case of an axle load of 7.5 tonnes (the legal limit for a tandem axle) and three tyre configurations: the 11R22.5 correctly inflated, the 11R22.5 inflated to 690 kPa, and the 235/75R17.5 correctly inflated. From the analysis presented in chapter 3.3 of this report, the net contact pressures and contact patch sizes can be determined, and from these the normalised peak subgrade strains can be calculated. All the strain values given so far relate to a single tyre.

In the case of dual tyres, the contribution to the strain from the adjacent tyre must be added on. Because of the width of the tread, the centre of load for this adjacent tyre must be more than 0.2 m from the centre of the tyre under consideration. Figure 5.2 shows that this contribution is not significantly affected by contact patch size. Both of these normalised strain values are given in Table 5.2. In the case of the dual tyres, the centre-to-centre tyre spacing is assumed to be 0.3 m.

Table 5.2 Normalised peak subgrade strains with different contact patch sizes.

Tyre size	Inflation pressure (kPa)	Net contact patch (m^2)	Peak strain (μs/kN)	Peak strain-dual tyres (μs/kN)
11R22.5	475	0.0387	25.36	33.44
11R22.5	690	0.0279	26.25	34.26
235/75R17.5	738	0.0210	27.15	35.09

From these results we see that a small diameter tyre generates 7% higher subgrade compressive strains than a correctly inflated 11R22.5 tyre for the same loading. However, over-inflating the standard tyre (to 690 kPa instead of 475 kPa) causes 3.5% higher compressive strains. When the dual tyre configuration is taken into account, these strain increases reduce to 5% and 2.5% respectively. All the results assume a circular contact patch and a uniform contact pressure. As the pavement response model is linear, then, if the contact patch size remains constant, the peak strain is directly proportional to the load. From Table 3.4 the changes in contact patch area with load are very small. Hence for small changes in load, the contact patch area can reasonably be assumed to remain constant. On this basis an axle fitted with small diameter dual tyres loaded to 7.14 tonnes (5%

reduction) is equivalent to a 7.5 tonne axle fitted with correctly inflated full size dual tyres. If the over-inflation of standard size tyres is taken into account, the equivalent load for the axle with small diameter tyres rises to 7.32 tonnes.

In terms of pavement wear, the design model assumes that pavement wear is proportional to approximately the fourth power of these pavement strain levels. On this basis, 5% and 2.5% increases in pavement strain would represent 21.5% and 10.4% increases in pavement wear respectively.

Using a different axle load or estimating gross contact patch areas does not change the relative magnitude of these results for small diameter tyres much, because the relative sizes of the contact patches stay similar. With higher axle loads, the degree of over-inflation of the standard tyre inflated to 690 kPa is less, and so the additional pavement strain caused is less, and conversely at lower loads the effect of over-inflation is greater.

Of interest also, Pidwerbesky (1996) measured the effect of inflation pressure on subgrade compressive strains at CAPTIF and found a small reduction in strain with increasing inflation pressure. This is somewhat counter-intuitive and contrary to the results of the modelling work undertaken here. No satisfactory explanation for these results has been postulated.

5.4 The Effect of a Non-Uniform Pressure Distribution

By a linear combination of the responses to different contact patch areas, a non-uniform contact pressure distribution can be simulated. However, as the VESYS model is based on circular symmetry about the centre of loading, a truly general 3-D distribution cannot be obtained without also offsetting the load centres.

In this section 5.4, a simple summation of a set of concentric contact patches, each at different contact pressures, is used to simulate a non-uniform contact pressure distribution. As the VESYS model is linear-elastic, the principle of linear superposition applies and these different load cases can be combined in this way. The sum of the responses is then used to estimate the importance of this non-uniformity effect. Table 5.3 shows the combination contact patch sizes and pressures used, and Figure 5.3 shows a diagram of the resulting contact pressure distribution.

Table 5.3 Combination of patch sizes and pressures used for the simulation.

Contact patch radius (mm)	12.7	25.4	38.1	50.8	63.5	76.2	88.9	101.6	114.3	127
Contact pressure (kPa)	5	10	30	55	75	90	100	110	120	300

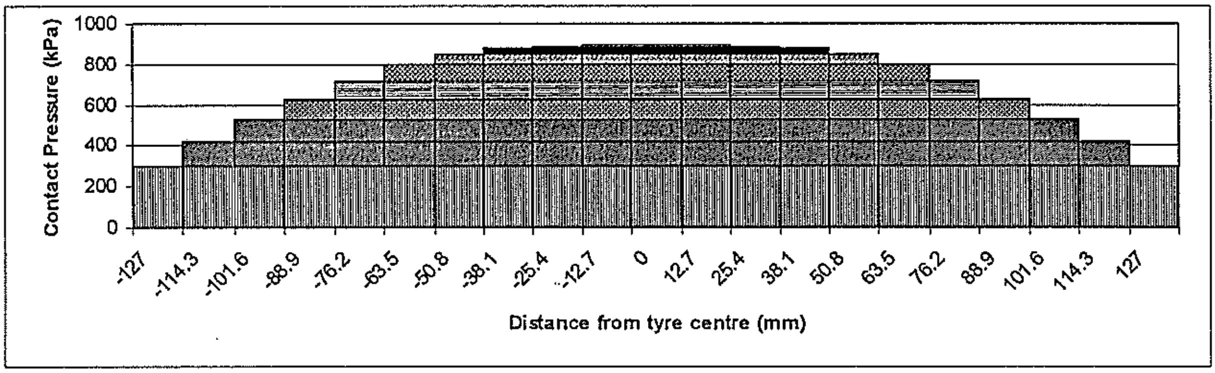

Figure 5.3 Pressure distribution resulting from combined patch sizes and pressures.

This corresponds to an average contact pressure of 580 kPa, with the peak contact pressure in the centre of the patch at 895 kPa, which is 54% higher than this mean. The shape of the contact pressure distribution for the combination is similar to that shown for the higher inflation pressures in Figures 3.2 and 3.3, which represent measured data. The combined peak compressive strain in the subgrade from this distribution is 2% higher than that obtained for a uniform contact pressure distribution of 580 kPa on a contact patch of 127 mm radius.

In practice, a completely uniform pressure distribution does not occur so the effect will tend to be smaller. When tyres are inflated to the recommended inflation pressure the contact pressure distribution is at its most uniform. There is no reason to expect that the shape of this distribution is any different for small diameter tyres and therefore, in comparing correctly inflated small diameter tyres with correctly inflated standard size tyres, we would not expect any impact from the non-uniformity of the contact pressure distribution. However, with an over-inflated tyre there is an increase in the non-uniformity of the contact pressure distribution. This will reduce the size of the difference in peak strain between over-inflated standard tyres and small diameter tyres.

5.5 Basecourse Compressive Strains

The discussion so far has concentrated on the level of the compressive strains in the subgrade because this is the basis for the pavement design model. However, in the last two accelerated pavement tests undertaken at CAPTIF, a significant amount of the rutting that occurred was in the basecourse layer. If the strains at the top of the basecourse layer are considered, we get the normalised strains shown in Figure 5.4. Comparing with Figure 5.2, which shows the subgrade strains under the same conditions, the pattern is similar in that the peak strains decrease with increasing patch size but shows a much greater effect from the contact patch size. Note that there is also a small tensile component at 0.15 – 0.2 m from the load application centre which is, of course, not possible for an unbound material.

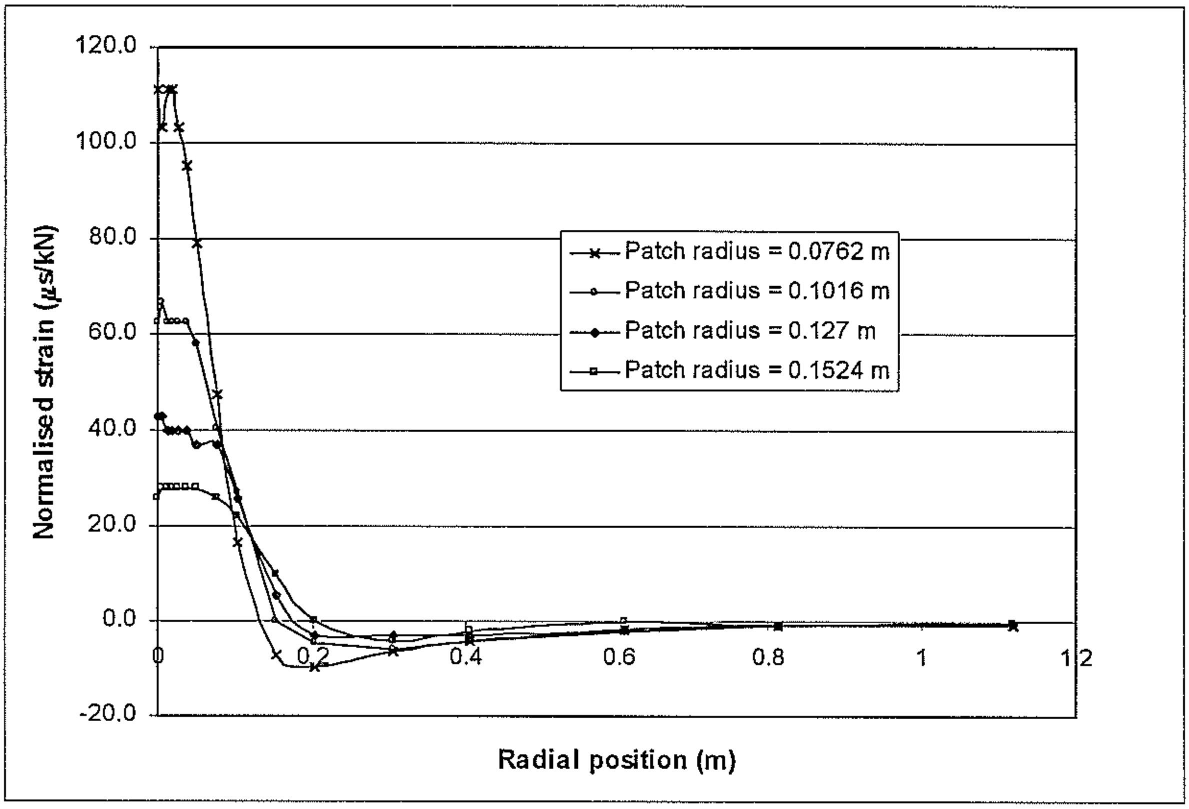

Figure 5.4 Normalised basecourse strains for the analysed pavement design for different contact patch sizes.

However, these strain values are the change in strain due to application of the load. There is an offset value to be added to these strains for the strains related to the mass of pavement materials and the initial compaction. This value ensures that the total compressive strain in the basecourse does not become negative.

Applying the same analysis as in chapter 5.3 of this report, we obtain the results for basecourse shown Table 5.4 which is directly comparable with Table 5.2. The effects of contact patch size on the basecourse compressive strains are very much larger than those for the subgrade (Table 5.2). The increase in the peak strain for a correctly inflated standard tyre to a correctly inflated small diameter tyre is now 72% (compared to a 7% increase in strains for the subgrade. If comparisons are made with the dual tyres, the situation now gets worse (76%) because the dual tyres reduce the overall strain levels without reducing the difference proportionately. As with the subgrade strains, over-inflated standard tyres give strains approximately halfway between correctly inflated standard tyres and small diameter tyres.

Table 5.4 Normalised peak basecourse strains with different tyres.

Tyre size	Inflation pressure (kPa)	Net contact patch (m)	Peak strain (μs/kN)	Peak strain-dual tyres (μs/kN)
11R22.5	475	0.0387	55.42	50.20
11R22.5	690	0.0279	75.13	69.24
235/75R17.5	738	0.0210	95.06	88.50

Using the same non-uniform contact pressure distribution as in chapter 5.5 gives a 41% increase in peak strains. This again is similar in magnitude to the effect of over-inflating standard tyres.

5.6 Pavement Design Factors

The results and discussion in this chapter have all been based on a primary response analysis of a single typical pavement design. To undertake a comprehensive analysis using a range of pavement designs covering the spectrum is beyond the scope of this work. However, it is appropriate to make some comment on what the likely effects of changes in the pavement design parameters would do to the results.

An increase in the thickness or modulus of the basecourse layer will reduce the peak strain levels in the subgrade. It will also reduce the influence of contact patch size. The converse is also true - in that a change in the subgrade modulus will affect the magnitude of the peak strains at the top of subgrade. However, such a change should not significantly alter the extent to which the strains are affected by contact patch size.

6. Summary & Conclusions

6.1 Summary

This study has investigated the impact of using small diameter tyres on pavement wear. It was deduced that small diameter tyres might impact on pavement wear through two possible mechanisms:

1. The smaller contact patch of small diameter tyres, operating at higher inflation pressures, thus apply higher contact stresses to the surface of the pavement which might result in greater pavement wear.
2. The vehicle dynamics influenced by the significantly lower mass of axles fitted with small diameter wheels and tyres. As the tyres are inflated to higher pressures they are also likely to be stiffer. These two factors affect the dynamic behaviour of the vehicle and the resulting wheel forces.

The findings of this study are summarised as follows:

- The use of small diameter tyres does not have a significant impact on dynamic wheel forces, and consequently on the pavement wear caused by dynamic wheel forces.

- With a pavement design that is typical for New Zealand roads, the use of small diameter tyres in a dual tyre set will generate peak compressive strains in the subgrade which are around 5% higher, than those generated by a correctly inflated standard size tyre. Based on the pavement design model, this 5% increase would correspond to an increase in pavement wear of around 21%.

- If the standard size tyre is over-inflated for its load (which seems to be common practice), it will, on the same pavement, generate peak compressive subgrade strains which are around 2.5% greater than those generated by the correctly inflated tyre. Furthermore if the change in contact pressure distribution is taken into account, these strains could be up to 2% greater again which is very similar to the situation with small diameter tyres.

- Over-inflating small diameter tyres will similarly have a detrimental effect on subgrade strains and pavement wear. As the recommended inflation pressures for these tyres are higher for the same loads, the level of over-inflation is likely to be less.

- Increasing the thickness (or modulus) of the upper pavement layers reduces the impact of contact patch size and pressure distribution on the subgrade compressive strains. Thus the effects described in this report will be less for thicker, stronger pavements and greater for thinner, weaker pavements.

- The analysis of pavement wear is based on the premise that the compressive strain in the subgrade layer is the key to pavement performance. If, however, there is a contribution to pavement wear from permanent deformations of the basecourse layer, the effects of contact patch size and pressure distribution are far more significant. The effect of using small diameter tyres, rather than correctly inflated standard tyres, on the peak compressive strain at the top of the basecourse is an increase in peak strain of around 76%.

6.2 Conclusions

The use of correctly inflated small diameter tyres would be expected to generate an increase in pavement wear when compared to correctly inflated standard size tyres. The scale of this additional wear is of the same order of magnitude as that generated by over-inflating standard tyres to the levels that are common in practice.

For future research the extent to which operators over-inflate tyres, and their rationale for doing so would be worth investigating. The practice appears to have no real benefits to them and it has a negative effect on the pavement infrastructure.

An appropriate education programme aimed at encouraging operators to use correct inflation pressures could result in substantial savings in pavement wear costs without any additional expenditure.

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