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TYRE SCUFFING FORCES FROM MULTI-AXLE GROUPS

Obtained BSc, BE(hons) and ME degrees from the University of Auckland and a PhD from Cambridge University. Currently Director of Engineering Research at TERNZ Ltd in Auckland, New Zealand.

Obtained BSc and MSc (hons) degrees in Physics from the University of Waikato. Currently a Transport Researcher at TERNZ Ltd.

John de PONT **Neon TARAMOEROA**

TERNZ Ltd
Manukau, New Zealand

Abstract

The management of pavement wear has primarily focused on distress caused by vertical loads. One of the ways of reducing the impact of vertical loading is to increase the number of axles and so we have seen an evolution from single axles to tandem, tridem and now, in some jurisdictions, quad axle groups. Multi-axle groups reduce the peak vertical loading and, when closely-spaced, reduce the magnitude of the strain cycles to which the pavement is subjected. However, during turning manoeuvres, particularly at low speed, they lead to increased shear forces at the pavement-tyre interface. The magnitude of the shear forces generated by multi-axle groups depends on many factors including the number of axles in the group, axle spacing, how many axles are steering, tyre size and configuration as well as vehicle geometry, suspension characteristics, vehicle speed, turn radius and angle of turn. This paper reports on a study that quantifies the magnitude of the impact of varying each of these parameters on the shear forces applied to the pavement surface.

Keywords: Vehicle-road interaction**,** Tyre forces, Multi-axle groups, Pavement wear, Axle spacing, Self-steering axles, Lateral load transfer.

Résumé

La gestion des dommages aux chaussées s’est surtout focalisée sur l’effet des charges verticales. Un moyen de réduire l’impact des charges verticales est d’augmenter le nombre d’essieux d’où l’évolution constatée des essieux simples aux tandem, tridem et maintenant, selon certaines législations, aux groupes d’essieux quadruples. Les groupes d’essieux multiples réduisent la charge verticale concentrée et, lorsque l’espacement entre essieux du groupe est faible, l’amplitude des cycles de déformation auxquels la chaussée est soumise est réduite. Cependant, lors des manœuvres de virage, notamment à faible vitesse, ces groupes d’essieux accroissent les efforts tranchants à l'interface pneu-chaussée. L’amplitude de ces efforts tranchants dépend de nombreux facteurs dont le nombre d’essieux du groupe, leur espacement, le nombre d’essieux directeurs, la taille et la configuration des pneus ainsi que la géométrie du véhicule, les caractéristiques des suspensions, la vitesse, le rayon et l’angle du virage. Ce papier présente une étude quantifiée des impacts des variations de chacun de ces paramètres sur les efforts tranchants appliqués à la surface des chaussées.

Mots-clés: Interaction route-véhicule, forces d’impact des pneus, groupes d’essieux multiples, dommage aux chaussées, espacement d’essieux, essieux directeurs, transfert de charge latéral.

1. Introduction

In many jurisdictions there has been a gradual increase in the size and weight of heavy vehicles over time. As weight increases, pavement wear increases and this is a concern for road controlling authorities who need to manage this and provide a serviceable network for their users. The management of pavement wear has primarily focused on distress caused by vertical loads. This includes cracking, rutting, and roughness. One of the ways of reducing the impact of vertical loading is to increase the number of axles and so we have seen an evolution from single axles to tandem, tridem, and in some jurisdictions, quadem or quad-axle groups. Multi-axle groups reduce the peak vertical loading and, when closely spaced, reduce the magnitudes of the strain cycles to which the pavement is subjected. However, where tight low speed turns are executed, non-steering axle groups lead to transverse shear forces at the pavement-tyre interface.

In New Zealand the most widely used pavement construction consists of an unbound granular structure with chipseal surfacing. The most heavily trafficked roads are typically surfaced with asphaltic concrete. On chipseal surfaces the shear forces at the tyre-surface interface can cause ravelling and/or polishing of the stones in both cases leading to a loss of skid resistance. Recent research suggests that the damage to chipseal surfaces increase in proportion to the maximum tensile strain raised to the 5th power (NTC, 2006). With asphaltic concrete pavements, tensile shear stresses in the pavement surface resulting from shear force at tyre-surface interface can cause surface cracking and ravelling (Jacobs and Moraal, 1992). Thus the increased use of non-steering axle groups is likely to result in increased pavement wear in the vicinity of intersections and roundabouts where tight low speed turns are executed. In New Zealand concern over these pavement damage effects has resulted in regulators requiring quad-axle groups to be fitted with two self-steering axles.

2. Methodology

The magnitude of the transverse shear forces generated by multi-axle groups depends on many factors including the number of non-steering and self-steering axles, axle weights, tyre size and configuration, suspension geometry and compliance, vehicle type, turn radius and turn angle. This study quantifies the impact of these parameters on the magnitudes of the transverse shear forces generated during low speed turns.

The analysis was primarily based on computer simulations using the Yaw-Roll multi-body software developed by the University of Michigan Transportation Institute (Gillespie et al , 1982). In Yaw-Roll the non-linear cornering force and aligning torque characteristics of the tyres are represented using a tabular format based on vertical load and slip angle. Models of a generic simple trailer were used to assess the effects of axle configuration, axle load, axle spread, wheelbase, and turn geometry on peak scuffing forces. Following this models of a range of typical heavy vehicle and tyre configurations currently used in New Zealand were used to simulate a range of low speed turns and the relative impact of the peak scuffing forces for the different vehicles were identified. The key vehicle and turn parameters that affect the magnitude of the scuffing forces were identified.

A field trial was undertaken to assess the level of scuffing force required to cause visible wear on the pavement surface and, to a limited extent, to validate the simulation models. The physical testing was done on a section of road that was formerly part of State Highway 1 but is now a local access road. The pavement construction was an unbound granular structure with chipseal surfacing. For this test a three-axle full trailer with a single-axle dolly was jack-knifed. The drawbar was towed at crawl speed in a direction perpendicular to the trailer's alignment and the towing force measured. This manoeuvre was repeated for a range of axle group loads, each time on a different section of the pavement so that the effect on the surface could be assessed. The assessment was limited to a visual inspection.

3. Analysis and Results

3.1 Lateral load transfers

To achieve a moment balance about the towing hitch, the tyres on the lead non-steering axle must experience the greater cornering force and slip angle than the other axle(s). For this reason the true axis of the group is always slightly aft of the geometric centre meaning that the effective wheelbase of the vehicle unit is longer than the geometric wheelbase. Increasing the axle spread slightly increases the effective wheelbase. The New Zealand Vehicle Dimensions and Mass Rule (LTSA, 2002) defines the axis of an axle group (with the same tyre configuration on all axles) as the geometric centre of the non-steering axles. This definition is also widely used in other jurisdictions and applies when "axis" is referred to in the rest of this paper.

One of the first observations from simulating low-speed turns was that there was a significant lateral load transfer on each axle within the group. For example, on a tandem axle group, there is a load shift from the inner to the outer wheels on the leading axle and from the outer to the inner wheels on the trailing axle. The turning manoeuvre was conducted at low speed so the lateral acceleration is negligible. Consequently the two load transfers roughly balance each other so there is no significant net outboard (or inboard) load transfer.

The two mechanisms for this load transfer are as follows:

1. When an axle group moves through a constant radius turn there is a point near the mid-point of the axle group that moves perpendicularly to the radius. The transverse line through this point is the true axis of the axle group. Axles that are forward of the axis are steering outboard of the turn while axles that are behind the axis are steering inboard of the turn as shown in Figure 1. Thus the axles induce transverse shear forces that act at the pavement-tyre interface. Since the roll centre of the suspension is some distance above the ground, a roll moment is induced at the roll centre. To maintain a moment balance about the roll centre, load must be transferred laterally from one side of an axle to the other. This lateral load transfer increases with increasing roll centre height, increasing axle spread, and with reducing tyre track width.
2. If the trailer hitch is above or below the roll centre height of the suspension the transverse component of the towing force will generate some body roll which will lead to a net inboard or outboard load transfer for the group. With small articulation angles this effect is usually relatively small although for extreme cases such as the field trial where the trailer was jack-knifed it does become significant.

The magnitude of this lateral load transfer can be quite substantial - up to 50% of the static load or more. Thus, even from a vertical loading perspective, the pavement wear implications are significant because with a fourth power wear relationship for a tandem axle set this implies 2.6 times as much wear (based on one wheel at 50% more load and one wheel at 50% less load). In terms of scuffing force the cornering forces generated by a tyre depend on the slip angle and the vertical load and so an increase in vertical load generates an increase in peak cornering forces. This is offset by reduced cornering forces at the wheel with reduced vertical load and so the significance of the load transfer for pavement scuffing damage depends on the pavement wear mechanism and the non-linearity of the relationship between cornering force and vertical load of the tyres.

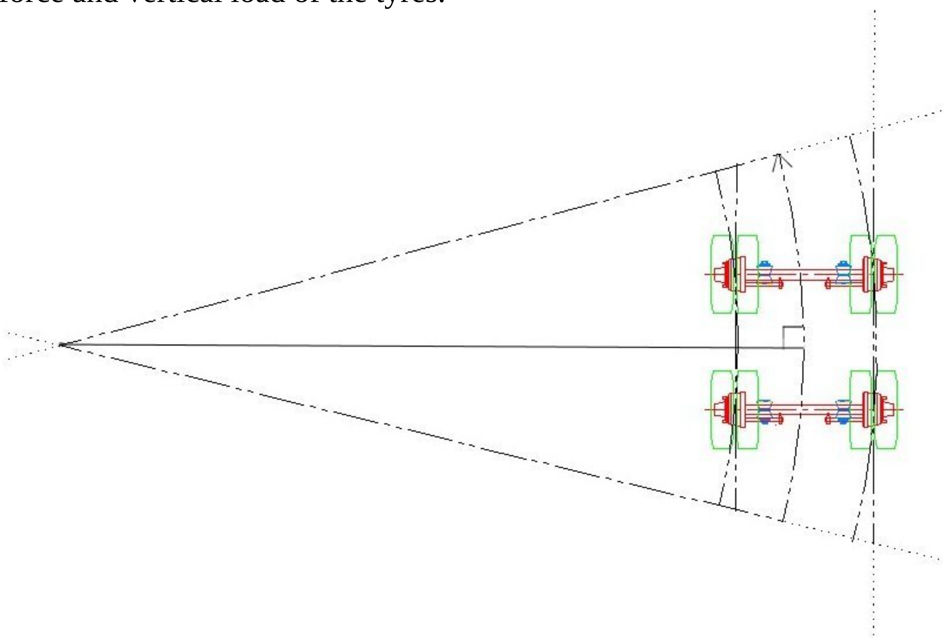

Figure 1 – Tandem axle set in a turn showing slip angles.

3.2 Effects of parameter changes

The first series of simulations used a model of a generic simple trailer with non-steering tandem and tridem axle groups to investigate the effect of various parameters on the magnitude of the scuffing forces. In this paper the discussion is limited to the tridem trailer case with the following parameters:

- angle of turn
- wheelbase
- axle spread
- axle weight

Figure 2 shows the peak scuffing forces for different levels of static load and axle group spacing during a 360° turn of 13.75m radius. The friction coefficient of the tyre-road interface was unity and the trailer forward length was 8.5m. Scuffing force increases with static weight and with axle group spacing as expected.

However, if we consider the ratio of peak scuffing force to peak vertical force as shown in Figure 3, we see the effect of the non-linear tyre characteristics with respect to vertical load. The peak scuffing force does not increase as rapidly as the peak vertical force.

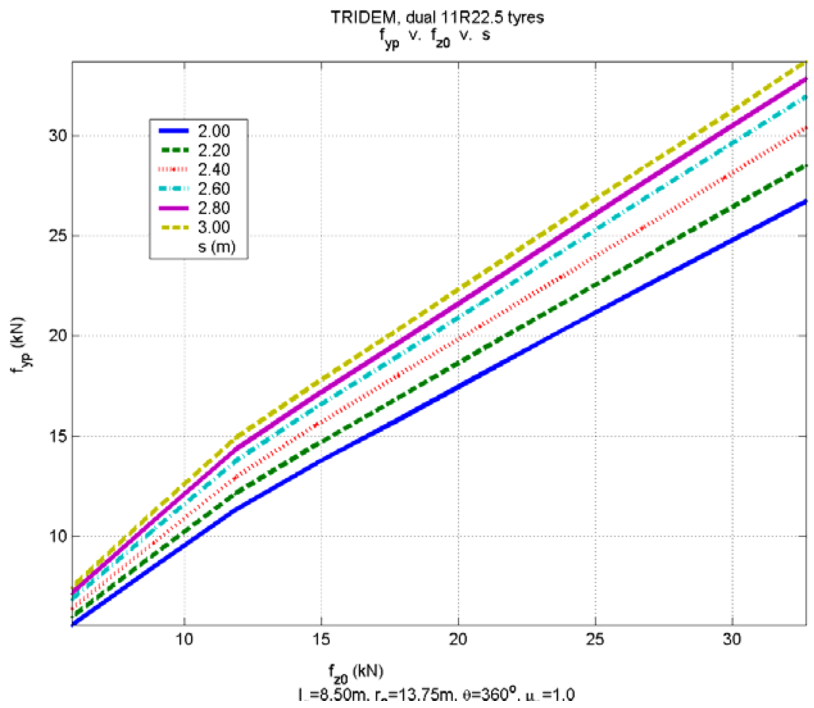

Figure 2 – Peak scuffing force against static load for different axle group spacing.

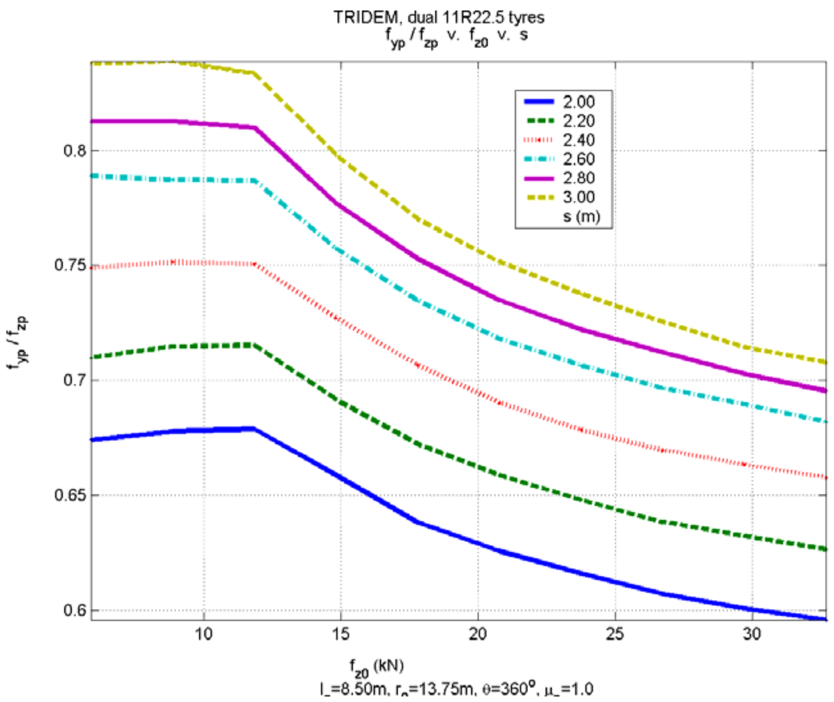

Figure 3 – Ratio of peak scuffing force to peak vertical force against static load.

Figure 4 shows the changes in peak scuffing force with increasing angles of turn for different trailer wheelbases. In all cases the axle group spacing is fixed at 2.5m, the turn radius of the towing hitch is 13.75m and the static wheel load is 29.42kN (3 tonnes). For turn angles less than approximately 120° the highest peak scuffing forces are generated by the shortest wheelbase vehicles. For greater turn angles the reverse applies with longer wheelbases generating higher peak scuffing forces. This result was somewhat surprising. Longer wheelbases result in greater offtracking for all turn angles and thus might have been expected to generate higher scuffing forces for all turn angles. However, longer wheelbase vehicles need a greater angle of turn to reach steady state offtracking and thus for smaller angles of turn do not achieve as small a turn radius as the shorter wheelbase vehicles. This result has important practical implications. Most on-road low speed turn situations involve turns with angles less than 120° and thus, for them, the critical vehicle for determining scuffing forces is the shortest wheelbase vehicle that would use the intersection not the longest. For combination vehicles the situation is more complex because leading vehicles affect the behaviour of trailing vehicles and the number and spacing of axles in a group also make a difference. However, as we shall see in the next section, this wheelbase effect means that for some combination vehicles the critical axle group is the tandem drive axle group on the prime mover rather than the trailer axle groups.

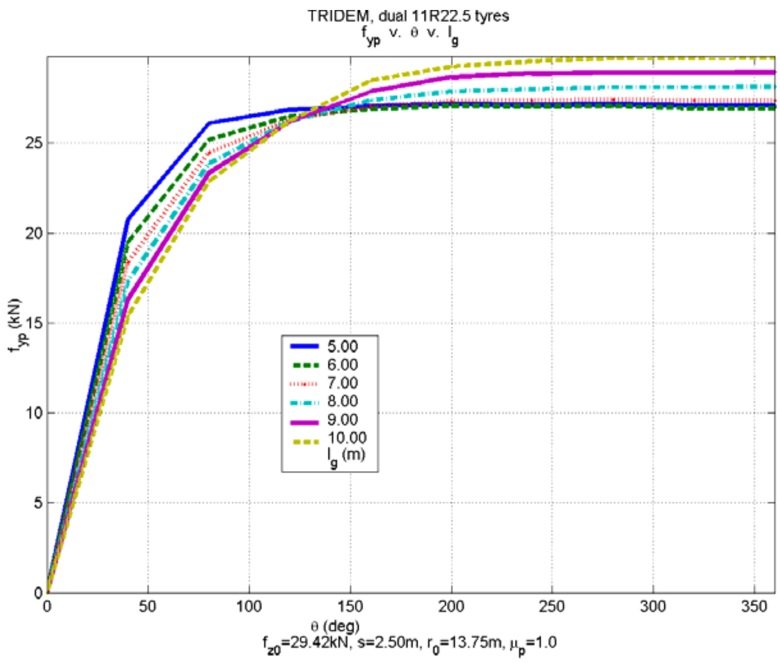

Figure 4 – Peak scuffing force against angle of turn for different wheelbases.

3.3 Scuffing forces from typical vehicles

A range of typical vehicles operating on New Zealand roads was simulated. The axle group loads were set at typical values. Most combination vehicles in New Zealand are limited by their gross combination weight limit (44 tonnes for the largest combinations) rather than the axle group weight limits and so the same axle group will operate at different weights when in different vehicle configurations.

Figure 5 shows the peak scuffing force generated by a selection of the most common vehicle configurations used in New Zealand against angle of turn. The quad-quad semitrailer and the 8-axle truck and trailer combinations both have twin-steer tandem drive prime movers while the other configurations all have single steer tandem drive units. In New Zealand quad-axle groups are required to have two self-steering axles (LTSA, 2002). Although these can be either the trailing two axles or the first and last axles, the requirements of the bridge formula and other dimensional constraints mean that, in practice the two self-steering axles are almost always the trailing two.

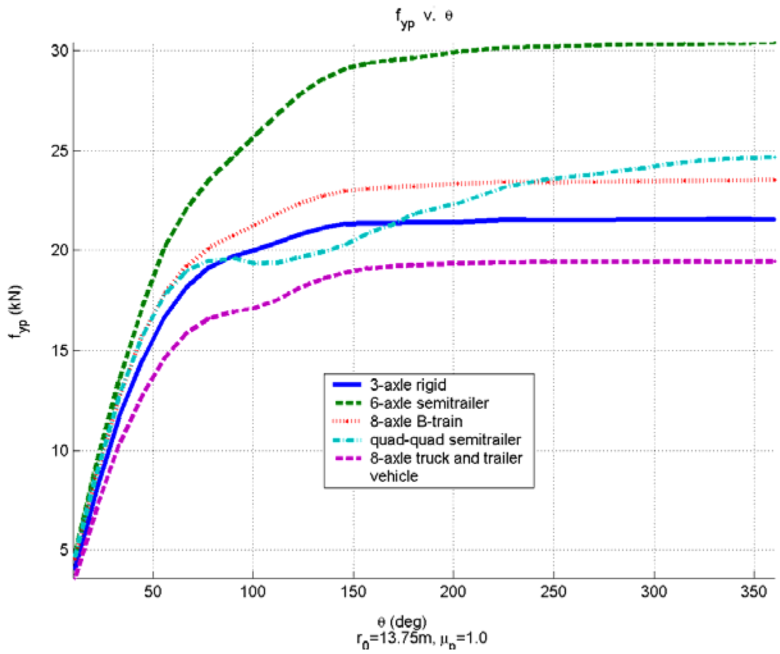

Figure 5 – Peak scuffing force against angle of turn for a selection of typical vehicles.

The highest scuffing forces are generated by the 6-axle semitrailer combination but as noted previously the axle group loads are not the same for each vehicle and the 6-axle semitrailer has the most heavily loaded tridem axle set.

In Figure 6 we have normalised the peak scuffing forces by the corresponding peak vertical force. This reduces the effect of having different weights on identical axle groups and in some ways presents a clearer picture. Essentially the vehicles fall into two groups; those with tandem axle groups only and those with tridem groups. The quad semi-trailer is essentially a tandem set initially because the two self-steering axles do not contribute any significant cornering force. At about 110° turn angle the self-steering axles reach their steering limits – the New Zealand regulations require a minimum of 15° of steer angle for the self-steering axles. At this point the axle group changes from being a tandem group to being a quad group and so the scuffing forces rise rapidly.

The curves for the quad-quad semitrailer and, to a lesser extent, the curve for the 8-axle truck and trailer show a dip in the peak forces at a turn angle of about 100°. These dips are the result of a change in the axle that is generating the peak scuffing force. As shown in Figure 4, for smaller angles of turn shorter wheelbase vehicles generate higher scuffing forces while for larger angles of turn longer wheelbases generate higher forces. For these two vehicles this effect means that the critical axle changes as the turn angle increases as illustrated in Table 1. For the quad-quad semitrailer, the highest scuffing forces are initially generated by the lead axle of the drive group on the prime mover but once the angle of turn is greater than about 110° the critical axle becomes the lead axle on the semitrailer. The situation then becomes more complicated because the self-steering axles reach their steering limits but the critical axle remains the lead axle of the quad set. For the truck and trailer combination, the critical axle initially is the lead axle on the dolly, which has the shortest wheelbase. Again at about 110° of turn the critical axle becomes the lead axle of the rear group on the trailer which has a longer wheelbase.

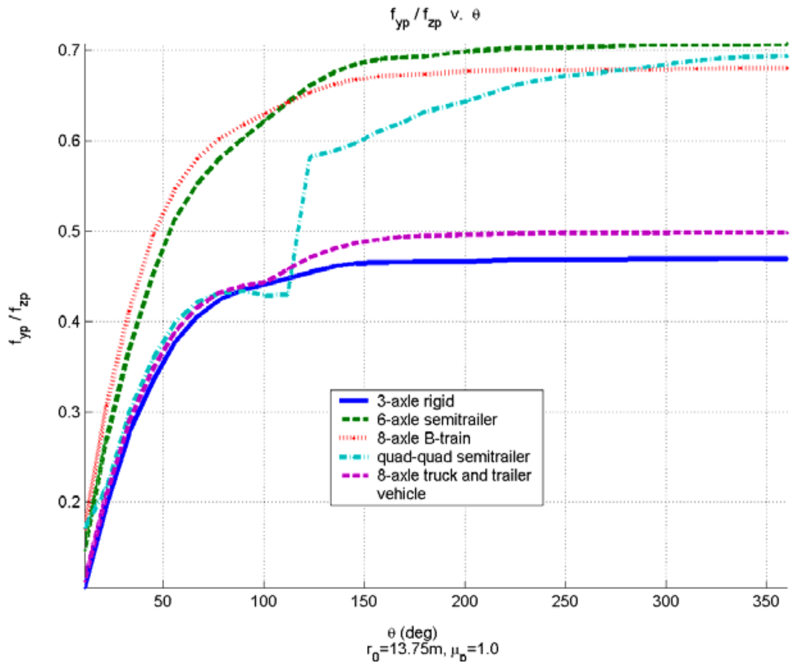

Figure 6 – Ratio of peak scuffing force to peak vertical force against angle of turn for a selection of typical vehicles.

Table 1 – Axle number generating the peak scuffing force.

Vehicle	Turn Angle							
	15°	30°	45°	60°	75°	90°	105°	120°
3-axle rigid	2	2	2	2	2	2	2	2
6-axle semitrailer	4	4	4	4	4	4	4	4
8-axle B-train	4	4	4	4	4	4	4	4
Quad-quad semitrailer	3	3	3	3	3	3	3	**5**
8-axle truck and trailer	5	5	5	5	5	5	5	**7**

3.4 Field trial results

As outlined in the methodology the field trial consisted of towing a 3-axle full trailer perpendicularly to its orientation and thus inducing pure scuffing in the tandem axle set at the rear. The towing forces required were measured for a range of vertical loads on the tandem group. The measured forces were compared with those predicted by a simple mechanics analysis of the force and moment balance and with those generated by a computer simulation model. In both cases the match was reasonably good. Figure 7 shows a comparison of the peak average scuffing forces measured during the field trial with those predicted by simulation for the different vertical load cases.

Minor visible damage to the pavement surface was observed even at the lowest vertical load. Small fragments were broken-off the exposed corners of the chip. This occurred when the vertical load on the tandem axle group was only 6920kg. From the computer simulation model this corresponds to peak scuffing forces of 36kN. Referring back to Figure 2 and Figure 5 we can see that the poorest performing vehicles generate scuffing forces that approach this magnitude.

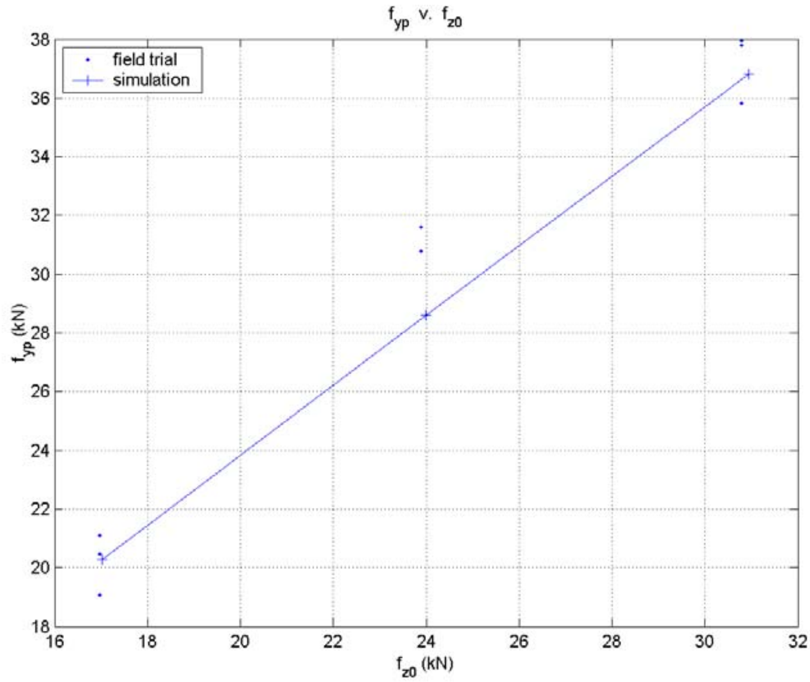

Figure 7 – Peak average scuffing force against vertical load.

4. Conclusions

This paper has presented a summary of some of the highlights of a detailed analysis of the factors affecting the scuffing forces applied to pavements by multi-axle groups undertaking low speed turns. Some key findings are:

- There is a significant lateral load transfer arising from the height of the suspension roll centre above the ground. This can be as much as 50% of the static load and thus increases the pavement wear due to vertical loading as well as increasing the scuffing forces which are also related to vertical loading.
- Non-linearity in the tyre response mitigates the effect on scuffing forces slightly because the scuffing forces do not rise quite as rapidly as the vertical forces for higher loads.
- For typical in-service angles of turn the highest scuffing forces are generated by shorter wheelbase vehicles because the longer wheelbase vehicles need a greater turn angle to reach steady state offtracking. For greater angles of turn (more than 120°) the reverse applies but these turn angles are not encountered very often in normal on-road operations.
- For typical vehicle configurations, tridem axle groups generate higher scuffing forces than tandem groups although this is affected by vertical load.
- Self-steering axles mitigate the scuffing forces substantially for smaller angles of turn but for large angles of turn they are likely to reach their steer angle limits at which time they respond like non-steering axles.

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