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# Pavement Damaging Effects of Road Trains

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Abstract

Australia's sealed rural road network consists predominantly of thin chip-sealed granular pavements. Concerns about accelerated damage to these pavements being caused by the expanding use of road trains and the continuing push for ever-larger vehicles have been supported by the findings of two recent sophisticated simulation studies. Traditional methods of estimating pavement damage due to the passage of vehicles consider only the effect of vertical loads - usually in terms of Equivalent Standard Axles (ESAs). A method based on computer modelling has been developed, which considers pavement damage under combined vertical, horizontal and moment loading imposed by each tyre of specific vehicles on specific pavement structures under a range of conditions that typify in-service operation. Five vehicles were investigated and their pavement damaging effects estimated: a rigid truck with a dual-tyred single "standard" axle loaded to 8.2t, a conventional six-axle prime mover and semi-trailer; and three different 53.5m long road trains. Using the tyre forces and moments imposed on the pavement surface for each vehicle as predicted by the computer models, the pavement responses were calculated using a linear elastic pavement layer response model that is capable of incorporating horizontal, vertical and moment loadings. Pavement response predictions were used to estimate the damage sustained by the individual components of the pavement structure by each tyre loading, and these damage results were accumulated over all axle groups and compared to those for the other vehicles in the same manoeuvres. The analysis found that increased damage would generally occur to the chip seal and basecourse layers for tri-axle drive road trains operating on grade and in turns (at intersections), which is consistent with in-service observations.

# 1. INTRODUCTION

Concerns about damage by road trains to existing thin chip seal pavements in Western Queensland in Australia has been supported by the findings of two recent sophisticated simulation studies of the pavement damaging effects of road trains.

The first study was commissioned by Queensland Department of Main Roads (QDMR) and considered pavement loading due to tri-axle and tandem-axle drive groups, largely ignoring damage due to the passage of the dollies and semi-trailer tyres (Prem and Potter, 1999). Its scope was to investigate one road train and compare its performance to that of a standard prime mover and semi-trailer. Further, the pavement structure specified for analysis was typical of that for the route taken by the six-trailer tri-axle drive vehicle being investigated, which was not necessarily typical of pavements on road train routes elsewhere in Australia.

The later study, also commissioned by QDMR, extended the earlier work and considered the complex pavement loading by entire road trains and damage due to all axles (prime-mover, dollies and semi-trailers) in the same set of manoeuvres (Ramsay, Potter and Prem, 1999). A larger range of vehicles was considered, which included a conventional tandem-drive triple road train and a four-trailer tri-axle drive road train[a], and a pavement structure that is more typical of thin chip-seal pavements in rural and remote areas of Australia.

This paper describes the approach and methodology employed, and presents the key findings from the two studies.

# 2. METHOD AND SCENARIOS

QDMR's main concern is the high tyre loads imposed on pavements by road trains and the resulting damage to thin chip seal pavements in turning areas (intersections) and on grades. Comprehensive full-vehicle computer models of five vehicles (shown in Table 1) were created by ARRB Transport Research Ltd. (ARRB TR) using the multi-body dynamic systems simulation package ADAMS (Mechanical Dynamics Inc, 2000). These were created in order to estimate pavement loading under all tyres in a number of scenarios that typify the operating conditions of principal concern.

Each vehicle model consisted of the following basic units: the prime-mover, the semi-trailer(s) and converter dollies. Each unit was built up from basic components (axles, suspensions, chassis, load, turntable, drawbar, etc.), and each component was constrained in the appropriate manner consistent with its normal operation in the real vehicle. Components were built up either from information supplied to ARRB TR by component and equipment manufacturers in the form of assembly and detailed engineering drawings or from first principles when these data were not available. Performance curves such as engine torque-speed characteristics, drive-train characteristics and suspension

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[a] Queensland Transport commissioned a separate supplementary study into the dynamics of four-trailer road trains, which is described in Ramsay, Prem and Brusza (2000).

characteristics were obtained direct from the manufacturers or from product brochures. Tyre property data were based on measured characteristics sourced from the tyre manufacturers as well as published literature. Speed and steer controllers developed by ARRB TR were used in the models to perform the various speed-related tasks and prescribed-path turning functions.

Validation of computer models used by ARRB TR has been performed by comparing measurements from full-scale tests with predictions from the models (Prem, Ramsay and Fletcher, 2000).

The models were used to estimate pavement loading under all tyres during the following simulated operating scenarios:

1) acceleration from rest along straight paths on level ground and on 2% and 5% uphill grades;
2) maximum constant speed on level ground and on 2% and 5% uphill grades; and
3) a 90° turn along a 15m radius curve at 10km/h (straight path entry and exit segments).

Using the forces and moments imposed on the pavement surface by the tyres as predicted by ADAMS, the pavement responses were calculated using CIRCLY (MINCAD Systems, 1997). CIRCLY is one of the few linear elastic pavement layer response models capable of incorporating horizontal loadings and moments as well as the vertical loadings that form the basis of traditional mechanistic pavement analysis procedures.

Pavement responses predicted by CIRCLY were then used to estimate the damage sustained by the individual components of the pavement structure by this loading. These damage results were accumulated over all axle groups and compared to those for the other vehicles in the same manoeuvre.

Worse case pavement loading conditions were identified for each scenario investigated, and the stresses and strains in the pavement were calculated at a number of locations within the pavement layers using comprehensive pavement response modelling software. The stresses and strains were then used to determine the relative pavement damaging effects of all axle groups associated with each vehicle.

# 3. VEHICLES AND TYRE LOADS

## 3.1 Vehicles

Five vehicles were considered in the two studies; a single-drive rigid truck with a 'standard' axle, a typical six-axle prime mover and semi-trailer, and three road-trains. These vehicles are shown in Table 1, and they are referred to in this paper as Rigid, Artic, A-Triple, AB-

Quad and 2B3, respectively. The key parameters for each vehicle are summarised in Table 2.

Worth noting in Table 2 is the decreasing power-to-weight ratio with increasing vehicle size. The traditional measure of pavement damage, namely, the number of Equivalent Standard Axles (using a Fourth-power law), or ESAs, which considers only the vertical loading, is seen to decrease on a per-unit-payload basis with increasing vehicle size, suggesting that pavement damage also decreases with increasing vehicle size. However, the tractive force exerted on the pavement by each drive tyre is seen to increase with vehicle size, and pavement damage due to horizontal loading at the drive group would be expected to increase with vehicle size. The extra tractive effort required by the heavier vehicles is necessary to accelerate them and to maintain reasonable speed on uphill grades; it is also required to overcome the additional resistance on level ground, on uphill grades and in turns from the larger number of tyres. Further, drive torque distribution within a tri-axle drive group can be quite complex, and the most common type was used in the two recent studies, which applies 50% of the available torque to the lead axle with the remaining 50% split equally between the centre and rear axles. As a result, the tractive effort will be much greater on the lead axle drive tyres than on the centre and rear axles tyres.

Finally, considering that the vertical load on a drive tyre[b] is typically 20kN for tandem and 16.3kN for tri-axle groups, all three road trains are each easily able to exceed the available tyre/road friction limits that would lead to wheel-spin.

## 3.2 Simulations, Tyre Forces and Pavement Loads

### 3.1.1 Starting from Rest on Grade

During start-up from rest, complicated transients and load transfers occur between tyres within a multiple-axle drive group. ADAMS was used to predict the peak tractive and vertical forces imposed on the pavement by individual tyres within the drive group during the start-up manoeuvres. Along straight paths the lateral tyre forces at all tyre locations at start-up and during constant speed travel are essentially zero and do not need to be considered.

During the simulations, it was found that for some vehicles it was possible to break traction if maximum torque was applied. To prevent this, the drive torque applied to the wheels was controlled, and limited, to achieve maximum traction without the onset of wheel-spin.

Figs. 1(a) and 1(b) show simulation results for the drive tractive effort and vehicle speed for the Artic starting from rest on 5% grade. The drive torque is introduced over a short period of time as the clutch is dis-engaged. As engine and vehicle speed increase, the

[b] Maximum axle loads applicable at the time of the analysis were used for the vehicels investigated, namely 6.0t on a steer axle (single tyres), 9.0t on a dual-tyred single axle, 16.5t on a tandem axle group, and 20.0t on a tri-axle group.

torque/speed response changes from a constant torque to a constant power characteristic, that is, torque decreases with speed as the driver selects higher gear ratios. The complicated transient dynamics of a gear change are not modelled, rather a constant power relationship is used, with the applied torque being inversely proportional to the vehicle speed.

Vertical and longitudinal tyre forces at start-up for the Artic and the AB-Quad are summarised in Tables 5(a) and 5(b). Results for the other vehicles can be found in Prem and Potter (1999), and in Ramsay, Potter and Prem (1999).

The results in Table 5(a) for vertical loads are typical, and show the tyres forces are approximately 50% higher (for the tandem drive Artic) and 30% higher (for the tri-axle drive AB-Quad) when compared with the static loads. As drive torque is applied, load is transferred from the steer axle and to the drive axles, as shown in Fig. 1(b). Further, for the same reason, vertical loads are not evenly distributed between drive axles, with the greater axle spread across the tri-axle drive group leading to a smaller transfer of load under the transient conditions.

The maximum tractive effort (longitudinal force) for the Artic and AB-Quad on each grade is presented in Table 5(b). Generally as the drive torque is applied, the front of the prime mover rises and load is transferred from the steer axle to the drive axles, particularly to the rearmost drive axle as shown in Fig. 1(b). The increased vertical load is able to sustain a higher tractive effort. Additionally, for the AB-Quad vehicle, the drive torque distribution between the three drive axles is such that approximately twice the tractive effort is applied to the lead drive axle compared to the centre and rear axles.

### 3.1.2 Constant Speed

As the vehicles accelerate from rest the drive torques decrease in accord with the torque-speed curves. Equilibrium is eventually reached whereby the resistive forces due to grade, tyre rolling resistance and aerodynamic drag exactly balance the tractive forces and a constant speed condition is reached. The vertical and longitudinal tyre loads during the steady-speed situation for the Artic and the AB-Quad are presented in Tables 5(a) and 5(b).

The vertical tyre forces for constant speed travel on grade are approximately equal to the static forces on level ground, whereas the longitudinal forces increase with grade, increase substantially with vehicle size, and depend on the distribution of torque between the drive axles. For example, the tractive force is approximately 3.5 times greater for the lead axle of the AB-Quad than for the Artic on a 5% uphill grade. Pavement damage generally follows a power law, so the horizontal loading from the much greater tractive force produced by the AB-Quad, for example, is expected to cause substantially greater pavement damage than the Artic (see later).

Due to the rolling resistance of the tyres, there is a small longitudinal force applied at the non-driven tyres (steer, trailer and dolly). This is typically 1% of the vertical load on the tyre, but does increase with increasing speed. A rolling resistance moment is also applied at the tyre/road interface that influences the pressure distribution within the contact patch. This moment is proportional to the vertical load on the tyre, so is not tabulated separately.

Typically, maximum start-up tractive forces for the road trains are approximately ten times those of steady speed operation on level ground. and about two times those of steady speed operation on 5% grade.

### 3.1.3 Low-Speed Turn

The low speed turn simulations are intended to represent movements at intersections. For the simulations it was assumed the vehicle travels at a constant speed of 10km/h and follows a 90°, 15m radius circular arc that has straight entry and exit segments.

The A-Triple road train is shown in Fig. 2 partway through a low-speed turn, where it can be clearly seen that, due to offtracking, the trailers will follow a different path to the prime mover. In the turn, the vehicle's tyres (and the pavement) are subjected to a complex combination of lateral, vertical and longitudinal forces. These three forces change during the turn, with each tyre being subjected to a different combination that will depend on the tyre's location on the vehicle (prime mover, dolly or semi-trailer), as well as its location within an axle group (front, centre or rear, inside or outside, and left/right side).

Additionally, the roll moment exerted on the axle due to tyre side forces will cause a transfer of vertical load from one side of the axle to the other. On the front axle of a tandem or tri-axle group this causes an increase in vertical load on the tyre closest to the turn centre, whereas on the rear axle the load increase will occur on the tyre furthest from the turn centre, as depicted in Fig. 3. This is discussed in more detail in Prem and Potter (1999) and Ramsay, Potter and Prem (1999).

Further, in a low-speed turn the steer tyres on a road train will closely follow the prescribed path but low-speed offtracking will cause the tyres on the rear axle of the last trailer to follow a path that has a much larger turn radius, thereby producing smaller side forces. The resultant horizontal force imposed on the pavement at each tyre location is the combined lateral (cornering) and longitudinal (tractive) forces generated at the tyre/road interface.

*a) Tyre Paths*

Figs 4(a) and 4(b) show plots of tyre paths for the Artic and the A-Triple in the low-speed turn manoeuvre, together with the locations of the maximum horizontal force and of the tyre path crossings (see later for how these locations were determined). For the larger vehicles, there is approximately 10m of offtracking, ie the rear trailer's tyres track some 10m inboard of the steer tyres.

The AB-Quad was found to be unable to accurately follow the 15m radius steering path. With 12 drive tyres spread over 3050mm, the two steer tyres are unable to generate sufficient lateral force to maintain the prime mover on the prescribed path. Investigations of this poor steering responsiveness of tri-axle drive prime movers have been undertaken in

Canada (Parker, Amlin and Hart, 1998), where it was concluded that increasing the load on the steer axle tyres or prime mover wheelbase, or decreasing the drive axle group spread had a beneficial effect on the steering responsiveness of the vehicle.

*b) Critical Locations*

When a tyre passes over a pavement, the pavement sustains damage not only directly under the tyre contact area but also adjacent to this contact area. To account for this in the exercise of determining critical pavement locations during the turn manoeuvre, the concept of a pseudo pavement loading was used. This concept involves imputing a transverse distribution to the tyre load of the form given in Eqn (1):

[Eq. 1] $$F(x) = Ae^{-(x/x_0)^2},$$

where $F(x)$ is the pseudo vertical force at radial distance $x$ from the centre-point of the tyre contact area. For the pavement under consideration, a value of 160mm was deemed appropriate for $x_0$. The adoption of this concept allowed critical locations to be determined as those locations which are subjected to the greatest cumulative pseudo vertical force.

Fig. 5(a) presents a plot of the force distribution under one tyre, at a given time during the low-speed turn manoeuvre (specifically when the tyre passes over the radial line that extends outward from the centre of the curve and is located 60° into the turn). The tyre passes over this line at a radius of 11,275 mm from the turn centre, and the tyre force distribution is centred on that radius.

This was repeated for all of the tyres on the vehicle (Artic has 22 tyres), and the results were accumulated, as shown in Fig. 5(b). The left (outside) steer tyre is seen to contribute to the distribution at the largest radius, and the three right (ie inside) trailer tyres pass through at the smallest radius.

At different angles, the tyre paths tend to cross each other, resulting in a superposition of individual responses. By definition, the maximum cumulative force occurs where the largest number of tyres pass over the same area.

This process is repeated for a range of angles into the turn, and the results superimposed, as shown in Fig. 5(c). The location of maximum cumulative force (and possibly the maximum damage) is assumed to occur at the radius and angle giving the highest cumulative force. In this case, the maximum cumulative force occurs close to an angle of 105° and a radius of 15,500 mm.

For each vehicle where tyre paths do cross (the rigid truck, having no trailers does not have any paths that cross), the locations of maximum cumulative force distribution were calculated. For the Artic, the steer, drive and trailer tyres cross on the 105° radial line at a radius of 15,670mm; at this location both the vertical and horizontal forces are greatest. For the AB-Quad, the drive, trailer1, dolly1, trailer2 and dolly2 tyres cross on the 135° radial line at a radius of 24,450mm.

These positions are also shown in Figs. 4(a) and 4(b) along with the tyre paths for the Artic and A-Triple vehicles, respectively.

For the turn manoeuvre, pavement analyses were conducted at both the locations where the maximum individual horizontal (and vertical) load occurs, and where multiple tyre paths cross. The maximum damage was taken to be the highest of the damage values determined at all these locations.

# 4. PAVEMENT DAMAGE

## 4.1 Review and Damage Estimation Procedure

In the development of a pavement damage estimation procedure both Australian and overseas practices were reviewed. Within Australia, the AUSTROADS Guide to the Structural Design of Road Pavements (AUSTROADS, 1992) is considered to be the flagship of pavement design. Hence, a review of its basis for assessing the damage caused by specific combinations of loads on axle groups was undertaken, and, in relation to the needs of the studies, the following shortcomings were noted:

i) no account is taken of horizontal loads applied to the pavement by the axle group;
ii) no account is taken of moments applied to the pavement through the tyre contact patch;
iii) no estimation of damage to a chip seal is provided; and
iv) damage caused to both the granular material and the subgrade of a chip-sealed granular pavement are combined in a single "overall" estimate of damage.

In the light of these considerable short-comings, for the studies undertaken it was considered that the AUSTROADS procedure was far from adequate. A review of overseas literature and practice unearthed very little of substance which would assist in establishing a damage estimation procedure relevant to the two studies.

In assembling a model for comparing the damage caused by axle groups, the basis of the mechanistic procedure for analysis of pavements was adopted as the most appropriate analysis framework. This basis consists of:

i) modelling the pavement as an idealised structure amenable to stress-strain analysis;
ii) determining the magnitudes of critical responses (stresses, strains) within the pavement caused by the pavement loading; and
iii) using the magnitudes of these critical responses in appropriate performance models to estimate pavement damage.

# 4.2 Pavement Response and Material Damage Models

### 4.2.1 Pavement Response Model

While there is a broad range of response models available (finite element models, linear visco-elastic models, etc.), the model in common use for pavement analysis is the linear elastic model wherein each pavement layer is modelled as a linear elastic material of infinite extent in both horizontal directions. In addition, the subgrade (roadbed) is considered to be infinitely deep. Such a model – with its admitted shortcomings – has been found to be quite adequate for estimation of peak transient responses within flexible pavements.

While many linear-elastic layer models are in use throughout the world, the Australian-developed CIRCLY (MINCAD Systems, 1997) is alone in its ability to incorporate both vertical and horizontal loadings and moments. Hence, in the two studies, CIRCLY was adopted as the response model to determine the magnitudes of critical pavement responses.

### 4.2.2 Material Damage Models

Separate damage models were adopted for each of the three components of the pavement – the chip seal, the basecourse, and the subgrade.

*a) Damage to chip seal*

Because there are no extant models for the performance of chip seals under horizontal loading, the following model was adopted:

[Eq. 2]

$$N \propto \left(\frac{1}{\mu\varepsilon}\right)^5$$

where:

$N$ = number of repetitions of a specific pavement loading before cracking of the seal occurs; and

$\mu\varepsilon$ = magnitude of the peak horizontal tensile strain generated in the seal by the passage of the load.

This model was adopted on the grounds that:

i) cracking of the seal after multiple passages of a load is attributable to fatigue fracture of the (bituminous) binder;
ii) fatigue cracking in asphalt involves a similar mechanism; and
iii) fatigue cracking in asphalt is well represented by the above model.

*b) Damage to the basecourse granular material*

Because of the significant horizontal forces being transmitted to the pavement by the drive axle group tyres, it was considered appropriate to investigate the likely effect of these on the performance of the granular basecourse material, ie the upper position of the granular material under the seal. As is the case with seals, models for the performance of granular basecourse layers are essentially non-existent. Based on laboratory investigations, Pell and Brown (1972) recommend the use of maximum tensile stress as the response parameter best suited to estimating the performance of granular materials. Freeme, Maree and Viljoen (1982) recommend the use of shear stress calculated at the mid-depth within the granular layer. In the early stages of development of a pavement design manual for QDMR, Baran and Aubrey (1978) found the criteria proposed by Pell and Brown (1972) to be consistent with the performance of chip-sealed pavements in Queensland. On the basis of this finding, together with broad acceptance of the stance by Pell and Brown (1972), maximum tensile stress was adopted as the appropriate basecourse response for use in this study.

The performance of granular materials subjected to repeated load passages involves transient breaking of the inter-particle frictional bonds in the matrix of the material – allowing relative movement of the constituent particles. The cumulative effect of the movements (after multiple load passes) is permanent deformation in the material, evidencing itself at the pavement surface as rutting and shoving.

The performance relationship for such a mechanism takes the form:

[Eq. 3] $$N \propto \left(\frac{1}{RESP}\right)^{K}$$

where:

$N$ = number of load repetitions on a specific pavement to produce a specified level of distress (usually a specified rut depth);

$RESP$ = maximum value of the critical response; and

$K$ = an appropriate constant.

Having adopted maximum tensile stress as the critical response, the issue of an appropriate value for $K$ remained. A value of 5 was adopted on the grounds that it represented a compromise between that proposed for use by AUSTROADS (1992) for the combined granular material and subgrade (value 7) and the value 4 associated with the Fourth Power Law.

On these grounds, the performance relationship adopted for the granular basecourse was:

[Eq. 4] $$N \propto \left(\frac{1}{\sigma}\right)^{5}$$

where:

$N =$ number of load repetitions which produces a specified contribution to the overall level of rutting and shoving; and

$\sigma =$ maximum horizontal tensile stress produced in the base-course by the load.

*c) Damage to the subgrade*

To compare damages caused by the axle groups in the lower regions of the pavement, the performance relationship proposed for use by Austroads for granular pavements was considered appropriate. The relationship is of the form:

[Eq. 5] $$N \propto \left(\frac{1}{\mu\varepsilon}\right)^7$$

where:

$N =$ number of load repetitions which produces a specified contribution to overall rutting and shoving; and

$\mu\varepsilon =$ maximum compressive vertical strain at the top of the subgrade produced by the load.

It is to be noted that the three performance relationships adopted are proportionality relationships – not equations. This is because the values of the proportionality constants needed to convert them to equations are not known. Their values obviously depend on the quality of pavement materials and construction, on the moisture regime within the pavement, etc. [For example, the "life" of a chip seal depends not only on the traffic it is subjected to but also on the quality of the seal (including its bond to the basecourse) and its temperature environment.]

As noted previously, when N repetitions of a specific loading occur before major rehabilitation is required, the damage caused by a single passage of the loading is 1/N. Hence, from the performance relationships given in performance relationships [2], [4] and [5], above, we have for a single passage:

[Eq. 6] $$\textit{chip seal damage} \propto \mu\varepsilon^5$$

[Eq. 7] $$\textit{basecourse damage} \propto \sigma^5$$

[Eq. 8] $$\textit{subgrade damage} \propto \mu\varepsilon^7$$

Because the constants of proportionality for these relationships are not known, they do not allow computation of the absolute damage (1/N).

However, because these constants only depend on pavement-specific properties, it is possible to make valid comparisons between the amount of damage caused to a given pavement element (seal or basecourse or subgrade) by different traffic loadings. The different traffic loadings may be caused by any combination of different axle groups or vehicles, speeds/accelerations, or road geometry.

For the case where the differences are solely due to the use of different axle groups, the comparison is appropriately reported as the *ratio* of damages attributable to the different axle groups.

For the case where the differences are attributable to broader combinations of factors, the comparisons are most appropriately made by reporting the damage values in arbitrary units – ie damage values calculated after an arbitrary value has been assigned to the (unknown) proportionality constant.

It is not possible to make comparisons between the damage caused to two distinct pavement elements (eg. seal and basecourse) within a pavement by the passage of a specific traffic loading.

# 5. REPRESENTATIVE PAVEMENTS

The general structure of the two pavements used in the two studies and the combination of vehicles and pavements investigated are summarised, respectively, in Tables 3 and 4. As noted earlier, the pavement structure specified in the Prem and Potter (1999) study was typical of a more heavily constructed pavement and is not necessarily typical of pavements on road train routes elsewhere in Australia. The pavement used in the second study (Ramsay, Potter and Prem, 1999) is considered more typical of thin chip-seal pavements in rural and remote areas of Australia.

The pavement selected for analysis in the second study and the locations within it where its responses to loading were determined are shown in Fig. 6.

For the chip seal, peak horizontal tensile strains were determined both at its surface and also at its base, ie at its bond with the granular basecourse. These two locations were chosen to encompass the two opposing theories of fracture of thin surfacings which are currently in vogue; one asserting that cracking initiates at the surface and progresses downwards, and the other asserting that it initiates at the bottom and progresses upwards.

For the granular basecourse, peak horizontal tensile stresses were determined at its upper surface and at depths of 25, 50, 100 mm within the material. These locations were selected in the expectation that damage would be most severe near the top of the material.

For the lower portion of the pavement, peak vertical compressive strains were determined at the top of the subgrade, in accordance with the AUSTROADS Guide procedure.

# 6. KEY FINDINGS

Straight-line operation of the vehicles predicted increasing tractive effort per tyre with increasing vehicle size, and with increasing grade. In accelerating from rest, tractive forces are similar between vehicles and on different grades, as the friction limit of the tyre/pavement interface dictated the maximum drive torque that could be used. In most cases, the tractive forces at start-up were some ten times greater than typical tractive forces for constant speed on level ground.

For the low speed turn manoeuvre the maximum horizontal force imposed by the tyres on the pavement was found to generally occur on the front axle of a tri-axle group, under the tyre closest to the inside of the turn. The lateral force generated by a tyre depends on the turn radius and on the axle group spread, increasing with axle group spread and as turn radius decreases, this force was greatest for tri-axle groups near the front of the vehicle.

The tri-axle drive (and tri-axle dolly) road trains were compared with their tandem-axle drive (and tandem-axle dolly) counterparts in a specific freight transport task on the basis of pavement damage per unit payload. It was found that at locations of start-up there would be substantial increase in chip seal damage, increase in basecourse damage, and a reduction in subgrade damage. In steady operation there would be increased chip seal damage on up-hill grades, negligible effect on flat terrain and a reduction in subgrade damage. At locations of tight turns there will be significant increases in both chip seal and basecourse damage.

Comparing the tandem-axle drive road train with a conventional tandem-axle drive prime mover and semi-trailers on the same basis shows that at locations of start-up there would be a significant reduction in chip seal, basecourse and subgrade damage. However, in steady operation on up-hill grades there would be increased damage in the chip seal and basecourse, but decreased subgrade damage on both flat terrain and on grade. At locations of tight turns, there are significant reductions in both chip seal and basecourse damage.

Overall, locations of increased pavement damage for the tri-axle drive road trains will be restricted to intersections, up-hill grades, and horizontal curves. Horizontal curvature on up-hill grades is a particularly undesirable combination of road geometry.

For the thin granular pavement analysed, the critical location in the chip seal is always at its surface. For travel on flat terrain and on moderate grades, basecourse damage is most severe at a depth of 100 mm or more within the material. However, on steep up-hill grades and in tight turns, the larger vehicles cause most basecourse damage at the top of the layer, and at start-up, the critical location in the basecourse is at its top.

At start-up and on up-hill grades the damage caused to the chip seal and basecourse by road trains is almost entirely attributable to their drive axle-groups.

The tandem-axle drive groups modelled in the study showed excellent damage sharing between the two drive axles in essentially all situations. However, the tri-axle drive group modelled in the study showed very poor damage sharing among its three drive axles both at start-up and (with the exception of subgrade damage) on steep grades. In all operations, a large proportion of the chip seal damage caused by the tri-axle drive group was attributable solely to its leading axle, due to the application of 50% of the available drive torque with the two other drive axles sharing equally the remaining 50%.

With all vehicles, there is significantly more damage to the chip seal and basecourse in start-up and tight turn operations than in steady travel.

In steady travel, damage to all pavement components increases with vehicle size and chip seal and basecourse damage increase significantly with up-hill grade.

# 7. ISSUES FOR FURTHER CONSIDERATION

1) Tri-axle drive groups that have unequal distribution of drive torque between axles and wide spread axles within an axle group should be discouraged. Further, tri-axle drive groups that have two driven axles and one "lazy" axle should also be discouraged.

2) Further study is required to improve knowledge about pavement loading and damage at intersections. In particular, more typical scenarios at intersections should be investigated such as start-up in a low-speed turn, which would be more damaging to pavements than constant speed turns because of the increased tractive effort required to accelerate the vehicle from rest.

3) The tyre force and pavement response predictions from this study should be confirmed by measurement. Preliminary field observations support the findings of the two studies described in this paper.

4) In light of these findings, consideration should be given to the effect of combined vertical and horizontal loading on damage to other pavement configurations.

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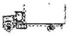
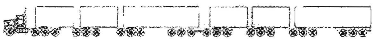
# TABLES AND FIGURES

TABLE 1 – Vehicles

| Abbreviated Name | Vehicle | Designation[1] |
|---|---|---|
| Rigid |  | 11 |
| Artic |  | 12S3 |
| A-Triple |  | 12S3(-2S3)2 |
| AB-Quad |  | 13S3-3S3-3(S3)2 |
| 2B3 |  | 13(S3)3-3(S3)3 |

Notes:
1) Description is based on the system proposed by Ramsay, Prem and Peters (2000)

TABLE 2 – Comparison of Vehicles

| Vehicle | Rigid | Artic | A-Triple | AB-Quad | 2B3 |
|---|---|---|---|---|---|
| Length (m) | 8.8 | 19.0 | 53.5 | 53.5 | 53.5 |
| GVM/GCM (t) | 12.3 | 42.5 | 115.5 | 146 | 166 |
| Payload (t) | 7.0 | 25.0 | 75.0 | 95 | 95 |
| ESAs | 1.3 | 5.0 | 11.8 | 11.2 | 12.6 |
| ESAs per Unit Payload (ESA/t) | 0.18 | 0.20 | 0.16 | 0.12 | 0.13 |
| Tyres | 6 | 22 | 62 | 86 | 98 |
| Driven Tyres | 4 | 8 | 8 | 12 | 12 |
| Power (kW) | 172 | 310 | 384 | 447 | 410 |
| Torque (Nm) | 895 | 1966 | 2516 | 2780 | 2508 |
| Power-to-Weight Ratio (kW/t) | 13.9 | 7.3 | 3.32 | 3.06 | 2.47 |
| Max. Tractive Force per Tyre (kN) | 21 | 20 | 37 | 46[1] | 47[1] |

Notes:
1) For leading axle of tri-axle group, which carries 50 % of the applied torque.

TABLE 3 – Pavement Configurations

| Pavement [a)] | Chip Seal | Basecourse [b)] | Subgrade |
|---|---|---|---|
| #1 | 25mm | 300mm | California Bearing Ratio of 5 |
| #2 | 10mm | 150mm | California Bearing Ratio of 10 |

Notes:

a) Pavement #1 was used in the study by Prem and Potter (1999), #2 was used in the study by Ramsay, Potter and Prem (1999)

b) Granular material

TABLE 4 – Vehicle/Pavement Combinations Investigated

| Vehicle | Pavement #1 | Pavement #2 |
|---|---|---|
| Rigid | ✖ | ✔ |
| Artic | ✔ | ✔ |
| A-Triple | ✖ | ✔ |
| AB-Quad | ✖ | ✔ |
| 2B3 | ✔ | ✖ |

TABLE 5(a) – Peak Vertical Forces in Straight-Path Manoeuvres

| Vehicle/Tyres | Vertical Force (kN) Start-up | | | Vertical Force (kN) Steady Speed | | |
|---|---|---|---|---|---|---|
| | 0% | 2% | 5% | 0% | 2% | 5% |
| **Artic** | | | | | | |
| Steer Tyres | 29.9 | 31.8 | 31.6 | 28.3 | 28.2 | 27.6 |
| Front Drive Tyres | 26.7 | 29.7 | 30.6 | 20.5 | 20.3 | 20.2 |
| Rear Drive Tyres | 27.2 | 29.1 | 30.5 | 20.5 | 20.3 | 20.2 |
| All Trailer Tyres | 16.3 | 16.5 | 16.6 | 16.3 | 16.4 | 16.6 |
| **AB-Quad** | | | | | | |
| Steer Tyres | 15.4 | 15.4 | 15.4 | 28.5 | 27.7 | 24.1 |
| Front Drive Tyres | 21.8 | 21.8 | 21.6 | 16.5 | 16.5 | 16.9 |
| Centre Drive Tyres | 18.0 | 17.9 | 17.8 | 16.5 | 16.5 | 16.9 |
| Rear Drive Tyres | 19.7 | 19.8 | 19.7 | 16.5 | 16.5 | 16.9 |
| All Trailer Tyres | 16.3 | 16.5 | 16.6 | 16.3 | 16.5 | 16.6 |
| All Dolly Tyres | 16.3 | 16.2 | 16.0 | 16.3 | 16.2 | 16.0 |

TABLE 5(b) – Peak Longitudinal Forces in Straight-Path Manoeuvres

| Vehicle/Tyres | Longitudinal Force (kN) Start-up | | | Longitudinal Force (kN) Steady Speed | | |
|---|---|---|---|---|---|---|
| | 0% | 2% | 5% | 0% | 2% | 5% |
| **Artic** | | | | | | |
| Steer Tyres | -0.13 | -0.13 | -0.13 | -0.25 | -0.22 | -0.19 |
| Front Drive Tyres | 19.7 | 19.8 | 19.9 | 0.79 | 1.55 | 2.90 |
| Rear Drive Tyres | 20.1 | 20.3 | 20.1 | 0.79 | 1.55 | 2.90 |
| All Trailer Tyres | -0.09 | -0.09 | -0.09 | -0.15 | -0.13 | -0.11 |
| **AB-Quad** | | | | | | |
| Steer Tyres | -0.14 | -0.14 | -0.13 | -0.24 | -0.19 | -0.16 |
| Front Drive Tyres | 17.1 | 17.2 | 16.4 | 1.76 | 4.72 | 9.95 |
| Centre Drive Tyres | 7.7 | 8.0 | 8.2 | 0.81 | 2.31 | 4.92 |
| Rear Drive Tyres | 7.7 | 8.1 | 8.1 | 0.81 | 2.31 | 4.92 |
| All Trailer Tyres | -0.09 | -0.09 | -0.09 | -0.14 | -0.11 | -0.10 |
| All Dolly Tyres | -0.09 | -0.09 | -0.09 | -0.14 | -0.11 | -0.10 |

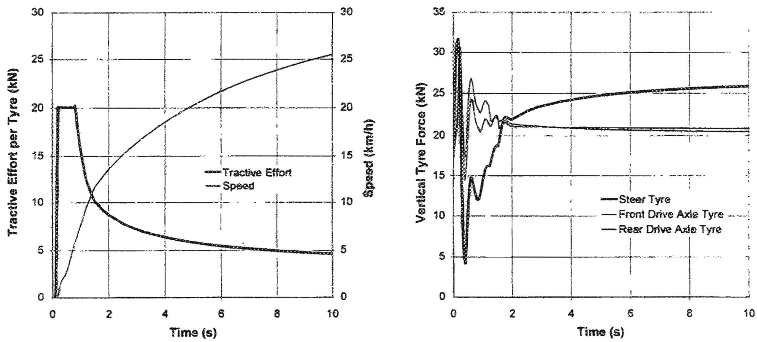



Fig. 1(a) Tractive effort and speed for Artic starting from rest on 5% grade.

Fig. 1(b) Change in tyre vertical load for Artic starting from rest on 5% grade.

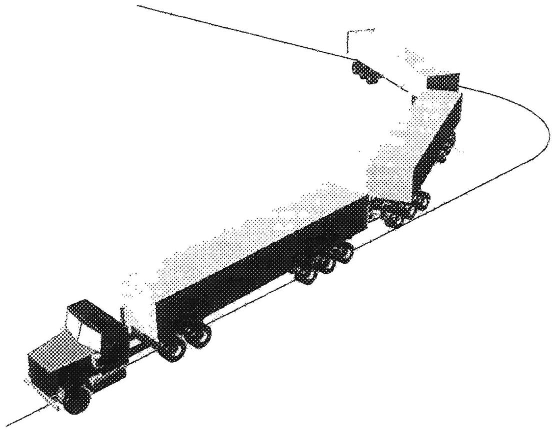


Fig. 2 A-Triple in a 15m radius low-speed turn (prescribed steer path shown as the fine line in the ground plane).

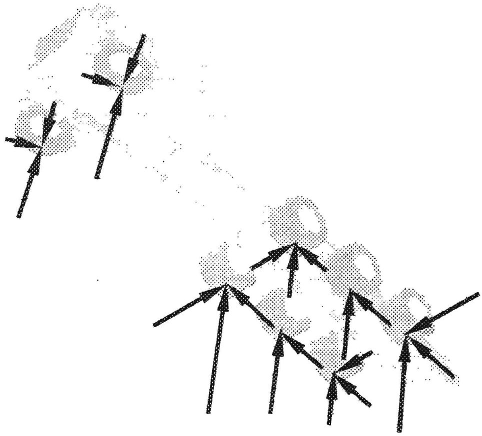


Fig. 3 Complex system of forces exerted on the steer and drive-axle group tyres during a low-speed turn to the right (tri-axle drive prime mover).

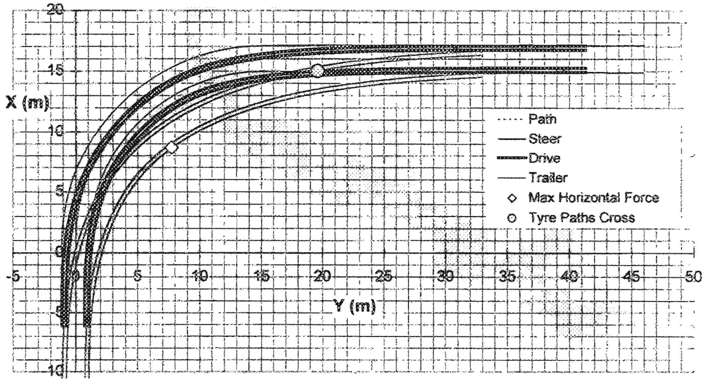



Fig. 4(a) Tyre paths and location of maximum horizontal tyre force for the Artic in a 15m radius turn.

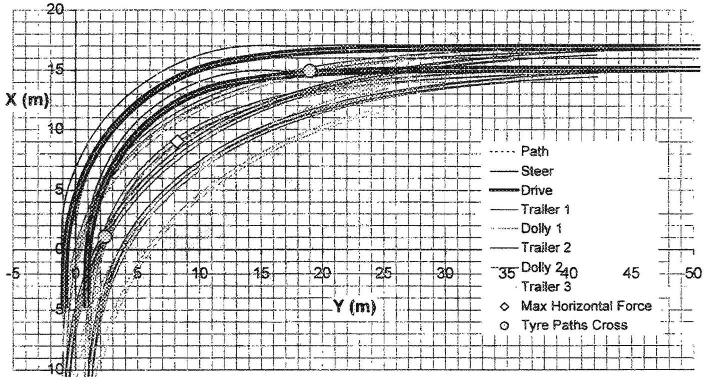



Fig. 4(b) Tyre paths for the A-Triple in a 15m radius turn.

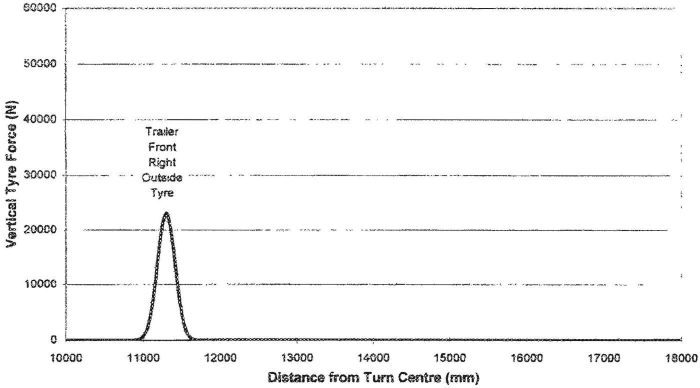



Fig. 5(a) Assumed force distribution under Artic trailer's front right outside tyre at 60° into the turn.

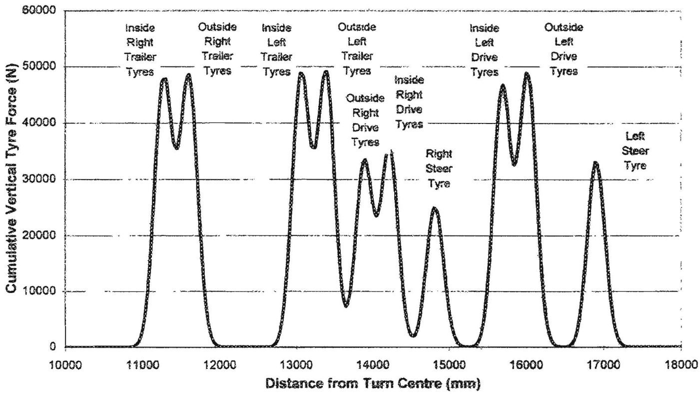



Fig. 5(b) Cumulative force distribution under all the Artic's tyres along the radial line that is 60° into the turn.

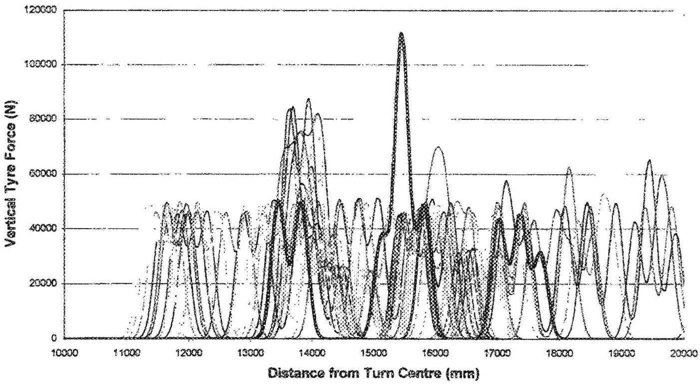



Fig. 5(c) Cumulative force distribution under all the Artic's tyres along radial lines across a wide range of angles over the entire turn.

| Location of Analysed Responses | Pavement Configuration | Thickness of (sub) layer (mm) | Elastic Characterisation: Degree of Anisotropy | (Vertical) Modulus (MPa) | Poisson's Ratio |
|---|---|---|---|---|---|
| CS | | | | | |
| CS, BC | Chip Seal | 10 | Isotropic | 1000 | 0.40 |
| BC 25 / BC 25 / BC | 150mm of granular material (CBR 45) | 30 | 2 | 230 | 0.35 |
| 50 | | 30 | 2 | 195 | 0.35 |
| BC | | 30 | 2 | 165 | 0.35 |
| | | 30 | 2 | 140 | 0.35 |
| | | 30 | 2 | 118 | 0.35 |
| SG | Subgrade (CBR 10) | Semi-Infinite | 2 | 100 | 0.45 |

Note: CS denotes chip seal, BC denotes basecourse, SG denotes subgrade.

Fig. 6 Pavement configuration adopted by Ramsay, Potter and Prem (1999), together with its elastic characterisation and locations of analysed responses.