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PERFORMANCE EVALUATION OF THE TRACKAXLE(TM) STEERABLE AXLE SYSTEM

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ABSTRACT

The use of steerable axles on heavy-vehicles is both a means of improving vehicle performance and a method of achieving higher productivity and improved access to the road network. The development in Australia and New Zealand of performance-based standards for the regulation of heavy vehicles provides one method of overcoming the prescriptive regulatory impediments to productivity and network access by directly addressing performance issues. Safety and infrastructure related performance measures were chosen from the set developed and proposed for use in Australia and applied to a new and novel steerable axle system known as "Trackaxle". The Trackaxle system, comprising a steerable axle group, allows increased trailer length by reducing low-speed offtracking. It utilises a rear, self-steering carriage rotating about its mid-point with respect to the trailer chassis. The front and rear of its three axles can oscillate with respect to the carriage in response to the angle developed between the body of the carriage and the trailer chassis. For on-road stability, the self-steer characteristic has two override devices: an automatic highway lock for straight ahead travel, and a spring loaded limiter system which controls the build-up of tyre side forces to limit the degree of rear-steer to a proportion of the articulation of the tractor at the fifth wheel. In the evaluation, full-vehicle computer-based models were created of a representative baseline prime-mover and semi-trailer combination, and another of a near identical vehicle featuring a longer semi-trailer equipped with the Trackaxle system. When compared to the baseline vehicle, the performance of Trackaxle was estimated to be better in several areas, including low-speed offtracking and horizontal tyre forces in a turn; the horizontal tyre forces were found to be low, suggesting a potential for reductions in pavement damage and wear. The evaluation of the prototype Trackaxle system indicates a range of potential benefits in the areas of safety, infrastructure and productivity, and illustrates a practical application of performance-based standards.

1. INTRODUCTION

The development in Australia and New Zealand of performance-based standards for heavy vehicle regulation provides one method of overcoming the current prescriptive regulatory impediments to innovation, productivity and network access by directly addressing safety and infrastructure related performance issues. By addressing performance issues rather than imposing constraints that are strongly linked to dimensions and mass limits, specific performance outcomes can be achieved.

One area of innovation with the potential to improve vehicle performance and productivity involves the use of steerable axles. While the focus of this paper is on steerable trailer axles, the use of steerable axles could also include drive axle groups.

The purpose of this paper is twofold. It presents both a technical description of the steerable trailer axle system known as "Trackaxle", and an evaluation of its performance using a performance-based standards approach. The evaluation draws on the most recent work and recommendations from a major initiative by Austroads[1] and the National Road Transport Commission (NRTC) in Australia in the area of performance based standards (National Road Transport Commission, 2002).

2. LOW-SPEED OFFTRACKING AND STEERABLE AXLES

2.1 Conventional Articulated Vehicles

It is known that for conventional articulated vehicles the amount of offtracking that occurs in a low-speed turn depends upon truck/prime-mover and trailer wheelbases, hitch locations and the lengths between articulation

[1] Austroads is the association of Australian and New Zealand road transport and traffic authorities.

points. The dependence varies with the squares of the lengths, and the longest trailer wheelbase is a critical parameter in determining the level of offtracking. Including additional articulation points to reduce the lengths of the longest wheelbases, and making trailer lengths equal in multi-unit combinations can achieve improvements in offtracking (Fancher et al, 1989).

2.2 Steerable trailer Axles

Another means of reducing the offtracking behaviour of articulated vehicles in low-speed turns involves the use of steerable trailer axles. Steerable trailer axles allow long-length trailers to be optimised to operate within the geometric design constraints of intersections and the road network. While increased length trailers with greater cubic capacity and improved road access have obvious and direct productivity outcomes, the less obvious benefits of steerable trailer axles are reported to be reduction in tyre scrub and tyre wear, as well as pavement wear. These in turn are claimed to lead to lower fuel consumption and reduced exhaust emissions (Gayat, 2000a).

3. "TRACKAXLE" AND ITS EVALUATION

3.1 Background

Gayat Pty Ltd has developed a steerable axle group that is designed to follow the swept path of the prime mover or other preceding vehicle wheel group. The system is referred to as "Trackaxle"[2], and derives its steering characteristics from a combination of force (linkage) steered and free steered sub-systems. For operation at highway speeds a mechanism locks the axles in the straight-ahead position.

A prototype semi-trailer featuring the Trackaxle system has been manufactured and field trails have been conducted. The prototype unit was compared to a similar conventional articulated vehicle in the field trails, and both a reduced low-speed offtracking and an acceptable tracking ability at highway speed have been demonstrated. To further test the performance of Trackaxle in everyday use and to assess the behaviour and responses of other road users with respect to areas of potential conflict, as described in Prem and Ramsay (2001b), in-traffic pilot trials are now underway.

As lead-up to the pilot trials, a detailed evaluation was carried out of the Trackaxle performance. The objective was to determine how the system would perform in a wide range of operating conditions and in standard manoeuvres. In particular, it was considered essential to assess both the safety-related performance as well as impacts on the infrastructure. This objective was met by using a combination of performance-based standards – drawing on the most recent work on performance-based standards by Austroads and the NRTC – and computer-based modelling and simulation.

It is important to note that the work described in this paper does not address any issues related to the mechanical strength of components, their durability and longevity, or their suitability to a particular application.

3.2 Methodology

Computer-based models were created of a representative baseline 19m long prime mover and semi-trailer combination, and another of a near identical vehicle featuring a longer semi-trailer equipped with the Trackaxle system. Safety and infrastructure related performance measures were chosen from the proposed final set of performance-based standards developed by Austroads and the NRTC and applied to the two vehicles. These standards are fully described in Prem et al (2001) and Prem et al (2002).

Simulations were performed with the two computer-based models in manoeuvres corresponding to each of the selected performance measures.

Outputs from the simulations were processed and performance was evaluated both in relative terms, by comparing the performance of Trackaxle to that of the baseline vehicle, and in absolute terms by comparing the performance of Trackaxle against the performance requirements of the selected standards.

In the analysis the performance of Trackaxle was considered acceptable if it met the proposed NRTC/Austroads standard. If Trackaxle met both the Austroads/NRTC standard and its performance exceeded that of the

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[2] Gayat Pty Ltd has lodged a provisional specification for a patent (Gayat, 2000b).

benchmark vehicle then its performance was described as better. If its performance was less than the baseline vehicle then its performance was described as worse.

4. PERFORMANCE-BASED STANDARDS APPROACH

4.1 Considerations and Recent Developments

A performance based standards approach to the regulation of heavy vehicles involves specifying or identifying desired outcomes, setting objectives to achieve those desired outcomes, and establishing performance measures that promote those objectives (ARRB Transport Research Ltd., 2000).

A set of performance standards have been developed by Austroads and the NRTC that define performance requirements that should be met if a vehicle is to be considered both safe for operation on the road network and acceptable in terms of wear to the infrastructure. While it is desirable for vehicles that are acceptable in terms of safety and infrastructure performance to also be more productive than equivalent currently operating vehicles, improved productivity is not the fundamental purpose of performance-based standards. Therefore, when the safety and infrastructure related impacts have not been compromised acceptable performance is considered to have been achieved (National Road Transport Commission, 2002).

Under the current prescriptive regulations the vehicle featuring the Trackaxle system as described in this paper would exceed the 19m overall length limit for general access to the road network. On length alone it could be disqualified from receiving general access status. However, under a performance based standards regulatory regime, overall length – while important in some on-road situations – is not a prime determinant in all situations of whether a vehicle is acceptable or not, or whether access should be restricted to specific parts of the road network. The range of performance measures developed by Austroads and the NRTC are designed to test a vehicle's safety-related performance, to assess its ability to fit within the road network, and to determine its impact on the infrastructure.

4.2 Selection of Performance Measures

Of the recommended final set of twenty (20) performance measures from Prem et al (2002), fifteen (15) have been developed to a stage where they are considered to be useable and suitable for regulatory purposes. Of those fifteen (15), the following seven (7) were selected for this paper - these are described briefly in Section 7:

- i) Low-Speed Offtracking
- ii) Tail Swing
- iii) Static Rollover Threshold
- iv) Rearward Amplification
- v) Yaw Damping Coefficient
- vi) High Speed Transient Offtracking
- vii) Horizontal Tyre Forces

The above set of performance measures was chosen on the basis that they would show the greatest contrast between the Trackaxle system and the baseline vehicle considered. A number of performance measures were not considered in this paper. Analysis from a previous study estimated these would be identical or near identical for the two vehicles. The performance measures that were not considered included, for example, startability, gradeability, acceleration capability, frontal swing and steer tyre friction demand.

5. TECHNICAL DESCRIPTION OF TRACKAXLE

A general description of the Trackaxle system and details of its key technical features is presented in this section of the paper. Further details can be found in Gayat (2000a) and Gayat (2000b). In order to interpret the performance of the Trackaxle system it was necessary to first develop a basic understanding of how the system works.

5.1 General Description and Design Goals

Gayat (2000a) describes Trackaxle as:

> *"An improved trailer axle group, self-steering tracking system designed to closely follow the narrow swept path of a leading prime mover or other preceding vehicle wheel group with a limiting system to prevent excessive rear steer at highway speed."*

Following are the six objectives the design needed to satisfy. These were set by the developer of Trackaxle,:

i) It must result in a major reduction in low-speed offtracking;
ii) It must reduce tyre and pavement wear;
iii) It must be stable on a highway;
iv) It must have few moving parts;
v) As much as possible, it must employ standard componentry; and
vi) It must not diminish lateral stability.

Fig. 1 provides a rear view of the prototype vehicle partway through a turn. This shows clearly the most obvious feature of Trackaxle; a trailer axle group that steers relative to the trailer chassis. In field trails this feature has been demonstrated to reduce low-speed offtracking, as illustrated in the photo sequence shown in Fig. 2, showing the prototype vehicle negotiating an urban roundabout.

5.2 Technical Detail

5.2.1 Components

The key components and sub-assemblies of the Trackaxle system comprise:

- the subframe that supports the axle group;
- control (linkages) rods that limit or modify the steer of the subframe;
- mechanisms that steer the subframe via the front and rear axles of the axle group[3];
- the mechanism that engages the tow-coupling turntable of the prime mover; and
- the steer control and steer limiter mechanism.

These components and sub-assemblies, which are described above, are identified in Fig 3.

5.2.2 Steer Response to Articulation Angle

As shown in Figs 3 and 4, a pair of linkages (rods) actuates the subframe (or bogie) steer mechanism allowing the subframe to rotate relative to the trailer chassis. The rods move in the fore-aft direction in response to the angle of articulation between the prime mover and the semi-trailer through the steer control and limiter mechanism (described later), which is shown in Fig. 6.

The basic relationship between subframe steer and articulation angle is shown in Fig. 5(a); this does not include the effect of the steer limiter.

In addition to steer rotation of the entire axle group through the subframe, the front and rear axles can be steered relative to the subframe by a pair of linkages (steer rods) through a connection to the centre axle. These steer rods are also shown in Fig. 4. The centre axle of the tri-axle group rotates with the subframe but is not steered relative to it. The basic relationship between subframe steer angle and the steer angle of the front and rear axles relative to the subframe is shown in Fig. 5(b).

As shown in Fig. 3, the subframe steer rods run the length of the semi-trailer between the centre of the trailer axle group and the tow-coupling turntable on the prime mover. The subframe steer rods are actuated by a mechanism controlling the angle of subframe on the trailer chassis. The mechanism has been designed to engage a standard turntable tow coupling (Gayat, 2000a).

5.2.3 Steer Control and Limiter

To cater for a wide range of on-road operating situations and conditions, the Trackaxle system also incorporates a number of design features that control and limit the degree of steering.

The steering actions transmitted along the subframe steer rods are generated by a slider/follower arrangement located at the tow coupling. These motions are modified under certain conditions by a steer limiter, comprising a pair of pre-loaded springs, with one located in each control rod. The slider follower arrangement and the steer limiter are identified in Fig. 6.

In order to keep the spring ends and the control rods a fixed length under certain conditions, the steer limiter springs are initially held in compression by a preload. When an axial compressive load exceeds the spring preload,

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[3] The links to the trailer body cause the front and rear axles to rotate in opposite directions, steering the subframe to follow the path of the prime-mover. This steering effect is opposite when the vehicle is reversing.

the length of the control rod decreases thereby modifying the simple steer relationship, shown in Fig. 5(a), between articulation angle and subframe angle. When active, the steer limiter permits a certain amount of self-steering, or free rotation to occur, in response to the yaw moment exerted on the subframe due to the build up of tyre side force. The force-displacement characteristics of the steer limiter are shown in Figs 7(a) and 7(b).

5.3.4 Highway Lock Pin

In addition to the above mechanisms for controlling trailer axle steer, a highway lock pin, as shown in Fig. 3, engages when the articulation angle is less than 2 degrees. When the highway lock pin is engaged the subframe and axle group are locked in the straight-ahead position, and the trailer behaves as if it were a conventional (long) trailer with a non-steered tri-axle group.

6. COMPUTER-BASED DYNAMIC MODELS AND SIMULATIONS

6.1 Vehicle Models

To evaluate Trackaxle the following two computer-based models were created using the ADAMS multi-body simulation software (Mechanical Dynamics, 2002) and the truck modelling toolbox developed by RTDynamics (RTDynamics, 2002a; 2002b). The models include controllers for speed[4] and steering as is required for many of the manoeuvres to be simulated:

- A baseline design prime mover and semi-trailer using dimensions of the Austroads design prime mover and semi-trailer (Austroads, 1995), having a 5.4 m wheelbase prime mover and a 13.7 m overall length semi-trailer.
- A prime mover and semi-trailer combination featuring the Trackaxle self-steering system as described in this paper, having the same 5.4 m wheelbase prime mover and a 15.81 m overall length semi-trailer.

The baseline vehicle has an overall length of 19.0 m, whereas the Trackaxle vehicle has an overall length of 21.08 m. Axle group loads for both vehicles were assumed to be identical and equal to the current legal limit for vehicles without road friendly suspensions. These loads are 6.0 t, 16.5 t and 20.0 t, on the steer axle and the drive and trailer axle groups, respectively, giving a gross mass of 42.5 t.

A generic, non-linear, full load-sharing air suspension model was used for both drive axle and trailer axle groups, the steer axle featured a non-linear multi-leaf steel spring suspension as proposed by Fancher et al (1980). 11R22.5 radial ply tyres were used on all wheels for both vehicles.

On the trailers a sprung mass centre-of-gravity (CG) height of 2.0 m was used, and it is an explicit assumption that this height was representative of worst case loading conditions.

The vehicle models described above are shown in Figs 8(a) and 8(b), respectively. Using the translucency features within ADAMS some of the detail incorporated in the Trackaxle system is revealed in Fig 8(b).

6.2 Simulations and Analysis

Both vehicle models were simulated using the test conditions and manoeuvres for the selected performance measures listed in Section 4.2 of this paper. Outputs from the simulations were post-processed and numeric values determined for each of the performance measures as defined in Prem et al (2002).

7. PERFORMANCE MEASURES AND RESULTS

This section of the paper briefly describes each of the performance measures considered, and presents the results of the simulations. The performance of the Trackaxle vehicle is compared with that of the baseline vehicle and the key results are presented in summary Tables 1 and 3. Table 2 is a summary of the performance standards used in this paper taken from Prem et al (2002).

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[4] Vehicle speed in the models is controlled through the application of tractive effort to the drive-axle tyres. Driveline characteristics in the model are generic and they are based on published engine torque-speed curves and gear reduction ratios.

7.1 Low-Speed Offtracking

For the simulation of low-speed offtracking the centre of the steer axle is required to follow a path comprising straight approaches to an 11.25 m radius 90° circular arc (Prem et al, 2002). This corresponds to the outside front wheel following a path of radius 12.5 m. A constant vehicle speed of 10 km/h is specified.

Trackaxle was found to have less low-speed offtracking than the baseline vehicle. For the baseline vehicle the maximum width of the swept path was 7.307 m, for Trackaxle it was 6.708 m. The swept path widths are less than the 7.4 m maximum for arterial road access, but neither is lower than the 5.0 m performance requirement to allow local roads access.

The low-speed offtracking simulations confirmed that for Trackaxle the path of the trailer axle group follows the swept path of the prime mover. This is consistent with the design goals of Trackaxle (Gayat, 2000a). The simulations also confirmed that for most of the turn less power was required by the Trackaxle prime mover to maintain the 10 km/h constant speed; approximately two-thirds of that required by the baseline vehicle towing the conventional trailer. This supports field observations and the claim of lower fuel consumption and exhaust emissions.

It is also worth noting that for the baseline (conventional) vehicle the location of the point of maximum offtracking through the turn occurs at a point that is near the centre of the rear axle group on the inside of the turn. For Trackaxle this point does not remain fixed at a single location relative to the vehicle, migrating forward from the rear axle during the initial stages of the turn and is well forward of the axle group at a point near the centre of the trailer body when offtracking reaches its maximum. These differences are illustrated in Fig. 9.

7.2 Tail Swing

For trailers with steerable axles, tail swing and low-speed steer behaviour will depend on the design goals set for the vehicle, how these goals are implemented in hardware, and how they are achieved in practice.

The Austroads/NRTC standards require tail swing to be evaluated on both approaches to the low-speed turn (entry and exit).

7.2.1 Turn Entry

On the entry to the turn, tail swing is greater for Trackaxle (0.325 m) than for the baseline vehicle (0.056 m). Fig. 10 illustrates and compares the difference in tracking between the baseline vehicle (upper illustration) and Trackaxle (lower illustration). It clearly shows how the baseline vehicle commences offtracking sooner, whereas Trackaxle initially holds a straighter path for a longer distance as it is steered relative to the trailer in response to articulation angle. This leads to a larger amount of tail swing, as recorded in the outputs of this performance measure.

Both vehicles are within the 0.35 m performance requirement specified by Austroads and the NRTC (Prem et al, 2002).

7.2.2 Turn Exit

Tail swing on the exit side of the turn is illustrated in Fig. 11, showing that the rear left corner of the Trackaxle trailer tracks approximately 0.275 m outside of the path of the front left corner of the prime mover when in the position shown. In practice, the driver would need to be aware of this overshoot and provide sufficient clearance to prevent the trailer from striking roadside objects that were successfully avoided by the prime mover.

For the baseline conventional vehicle (and other vehicles without steerable axles on trailers) tail swing on exit approach to the turn would not be an issue because the path of the rear left outside corner of the trailer approaches the path of the front left outside corner of the prime mover asymptotically.

Austroads and the NRTC (Prem et al, 2002) have specified the same performance level for tail swing on the exit, and both vehicles meet the 0.35 m performance requirement.

7.3 Static Rollover Threshold

To assess static rollover stability the vehicle is required to follow a circular path of constant radius (100 m). Test speed is slowly increased from 60 km/h until rollover occurs.

The first simulations under the prescribed conditions showed that the Trackaxle vehicle had a static rollover threshold of about 0.416 g. This was comparable to the value for the baseline vehicle, which was 0.417 g.

Gayat (2000a) claims that the increase in width of the tracking path of the trailer group when traversing curvatures and making sharp turns enhances rollover stability. This was attributed to the increase in "footprint" or effective track width when compared to a conventional tri-axle trailer group, as illustrated in Fig. 12.

To further explore this claim the simulations were repeated using a much smaller turn radius. This would increase the steer angle of the subframe and the corresponding width of the "footprint" with respect to the trailer.

On a turn radius of 20 m the static rollover threshold for the baseline and Trackaxle vehicles were estimated to be 0.410 g and 0.412 g, respectively. There was only a very small increase in rollover stability. The simulations showed the rollover stability of Trackaxle was expected to be similar to the baseline vehicle.

On close inspection of Fig. 12 it will be noted that while the effective track of the front axle on the left side of the Trackaxle system has increased, the effective track of the rear axle on the same side has decreased by a similar amount. The effective increase in track width, and corresponding increase in the roll stiffness on one axle, has been almost exactly offset by an opposite decrease in roll stiffness on another axle.

This result applies to a tri-axle group with identical roll stiffness on each axle and an idealised (perfect) load sharing airbag suspension. Increasing the roll stiffness on the front axle - either by increasing the auxiliary roll stiffness and/or the airbag spring rate - would better utilise the increase in effective track and this could lead to improvements in rollover stability. However, this would necessarily lead to greater front axle wheel loads. If implemented in Trackaxle it would need to be controlled and set at an appropriate level to ensure component loads did not exceed the manufacturer specified ratings. Hence, the potential for improving and enhancing rollover stability clearly exists, but the necessary design changes must take into account other aspects of the vehicle performance before being incorporated.

7.4 Rearward Amplification

Rearward Amplification (RA) is a measure of the tendency of the trailing unit(s) of an articulated vehicle to amplify any lateral acceleration experienced at the hauling unit. The performance requirement for RA set by Austroads and the NRTC, which assumes the SAE lane change is representative of a typical evasive manoeuvre, is defined in terms of the rollover stability of the critical, rearmost roll-coupled unit, as follows:

$$RA \quad 5.7SRT_{rrcu} \tag{1}$$

where:

RA = rearward amplification measured in accord with recommended practice SAE J2179 or ISO 14791 (-)

SRT_{rrcu} = static rollover threshold of the rearmost roll-coupled unit (g)

For a vehicle with a static rollover threshold of 0.35g, Eqn (1) sets the performance level for RA at 2.0, a performance level that is based on research carried out in the USA (Fancher et al, 1989; Winkler et al, 1992)[5]. Further, according to Eqn (1), larger values of RA are deemed to be acceptable only if accompanied by a commensurate increase in the rollover stability of the rearmost roll-coupled unit(s). Both SAE J2179 and ISO 14791 are accepted methods of testing, being well established and proven procedures that are fully documented (Society of Automotive Engineers, 1993; International Organisation for Standardisation, 2000). Further details on development of the revised performance level for RA can be found in Prem et al (2002).

In practical terms, a threshold value of 2.0 for RA means that the lateral (sideways) acceleration at the CG of the rearmost unit in the combination should not exceed twice the lateral acceleration at the centre of the steer axle of the hauling unit. In the SAE lane change manoeuvre the steer axle lateral acceleration has a peak value of 0.15g. Therefore, for the example cited, an RA that is less than 2.0 would be considered to be acceptable.

[5] During development of the Austroads/NRTC performance standards a set performance level of 2.0 for RA was also proposed (see Prem et al, 2001). However, the form described by Eqn (1) is preferred because it directly links the performance requirement to rollover stability, discussed fully in Prem et al (2002).

Both the baseline vehicle and Trackaxle were found to have acceptable rearward amplification and were well within the performance level value of 2.37 set by Eqn (1). Rearward amplification for Trackaxle, at 0.970, was lower than the value of 1.202 for the baseline vehicle. This is largely due to Trackaxle's longer trailer wheelbase, and there are no apparent adverse effects from Trackaxle.

7.5 Yaw Damping Coefficient

Yaw Damping Coefficient (YDC) quantifies how quickly oscillations of the last trailer take to reduce in amplitude, ie. settle, after the application of a short duration steer input at the hauling unit. Vehicles that take a long time to settle increase the driver's workload and represent a higher safety risk to other road users. Under the Austroads/NRTC performance standards (Prem et al, 2002) YDC is required not to be less than 0.15 to be considered acceptable.

YDC for both vehicles met the performance requirement by a factor greater than 3; for the baseline vehicle it was 0.533, and for Trackaxle it was lower at 0.487. As shown in Table 1, the steer limiter was active for this manoeuvre, ie, the highway lock was not engaged. While yaw damping is known to increase with trailer wheelbase (Prem et al, 2002), the increase in yaw damping with wheelbase is offset by the decrease in yaw damping due to Trackaxle. Consequently, with the highway lock engaged, yaw damping for Trackaxle would be expected to be greater than for the baseline vehicle.

7.6 High-Speed Transient Offtracking

High Speed Transient Offtracking (HSTO) measures how far the rear of the vehicle tracks outside the path taken by the hauling unit during the SAE lane change manoeuvre. The performance standard for HSTO requires that the centre of the rear of the trailer remain within 0.8 m of the path taken by the centre of the steer axle (Prem et al, 2001; Prem et al, 2002).

HSTO for both vehicles was found to be less than the specified 0.8 m performance requirement; the baseline vehicle having a lower value (0.201 m) than Trackaxle (0.365 m). With a longer trailer and the steer limiter active, there would be some steering of the trailer axle group leading to the increase in offtracking predicted by the simulations.

7.7 Horizontal Tyre Forces

This performance measure quantifies the influence of horizontal tyre forces on remaining pavement life. The same manoeuvre used for low-speed offtracking, described in Section 7.1, is also used for this measure. The performance measure can be applied to single and multi-axle groups as well as both driven and free-rolling wheels.

7.7.1 Lateral and Vertical Forces

Typical examples contrasting the key differences in tyre horizontal forces during the low-speed turn manoeuvre between the baseline and Trackaxle vehicles are shown in Fig. 13(a). These show the peak tyre side forces from Trackaxle to be more than 10 times lower than those for the baseline vehicle, and for the entire turn the forces are no greater than 1,450 N. This is a result of the Trackaxle system, achieving a balance between steer of the subframe in response to articulation angle, steer of the front and rear axles relative to the subframe, and characteristics of the steer limiter, which allows the subframe to self-steer along a path that reduces tyre side forces.

Prem and Potter (1999) found that on single axle and multi-axle groups the vertical tyre forces are modified by the horizontal side forces in a low-speed turn. The corresponding vertical forces for the two vehicles executing the low-speed turn are provided in Fig. 13(b), which shows that for Trackaxle the small change in tyre side force leads to a similarly small change in vertical force. For the baseline vehicle, however, the tyre side force imposes a roll moment on the axle resulting in a local increase in the vertical force on one side of the axle and a corresponding local decrease in vertical force on the other side, as shown in Fig. 13(b). In a low-speed turn on multi-axle group systems (two or more axles) there is a net increase in vertical load on tyres that are either at the front of the axle group and on the inside of the turn or at the rear of the axle group and on the outside of the turn, as discussed further in Prem and Potter (1999).

7.7.2 Tractive Forces

In a constant speed turn a reduction in tyre side forces would be reflected in a decrease in vehicle drag and a reduction in the tractive effort required to maintain a constant speed. The simulations showed that for most of the low-speed turn manoeuvre the tractive effort for Trackaxle was about 60% that of the baseline vehicle, and at times as low as 40%.

7.7.3 Pavement Damage (Wear)

The relative wear concept and the method described in Prem et al (2002), which is based on Prem and Potter (1999), was used to provide an indication of pavement wear due to horizontal forces, as required by this performance measure. The relative wear concept compares the estimated pavement damage (or wear) due to one vehicle (in this example Trackaxle) with that due to a representative reference vehicle; the Austroads design prime mover and semi-trailer.

Results for analysis of the horizontal forces, which are fully detailed in Prem and Ramsay (2001a), suggests that the Trackaxle tri-axle group, as described herein, will be between 160,000 and 190,000 times less damaging to the pavement than a conventional tri-axle group. It is important to note that the lower damage values for Trackaxle is due to the small side forces exerted on the pavement, as shown in Fig. 13(a), and on the use of a pavement surface layer damage model that is power law based involving horizontal tensile strain raised to the 5th power (Prem and Potter, 1999).

For the vertical forces the analysis suggests Trackaxle will be between 3.2 to 4.3 times less damaging than a conventional trailer with a non-steered tri-axle group.

The pavement damage values shown above for Trackaxle are presented relative to the baseline vehicle. The constants of proportionality for the damage relationships presented in Prem and Potter (1999) depend on pavement-specific properties. Because these constants are not known, they do not allow computation of absolute damage.

8. SUMMARY

A technical description of the steerable trailer axle system known as "Trackaxle" has been presented and an evaluation of its performance has been carried out using a performance-based standards approach and the performance standards developed by Austroads and the NRTC. Computer-based models were created of a representative baseline vehicle and another of a near identical vehicle with a longer semi-trailer and featuring the Trackaxle system. Safety and infrastructure related performance measures were chosen from the final set of measures developed by Austroads and the National Road Transport Commission (NRTC). These were applied to the two vehicles.

Performance of Trackaxle was evaluated both in relative terms, by comparing its performance to that of the baseline vehicle, and in absolute terms against the performance requirements of the selected Austroads/NRTC performance standards.

Trackaxle was able to meet all of the Austroads/NRTC performance standards that were considered. Its performance was found to be better than the baseline vehicle in respect of low-speed offtracking, rearward amplification, and pavement wear due to both horizontal and vertical tyre forces. Static rollover stability for both vehicles was similar. Compared to the baseline vehicle the performance of Trackaxle in respect of tail swing (on both the entry and exit approaches), yaw damping and high-speed transient offtracking was found to be worse.

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TABLES & FIGURES

Table 1 – Performance Summary

#	Performance Measure	Baseline Vehicle (OAL=19.00 m)	Trackaxle (OAL=21.08 m)	Steer Limiter
1	Low-Speed Offtracking	7.307 m	6.708 m	Active
2a	Tail Swing (turn entry)	0.056 m	0.325 m	Active
2b	Tail Swing (turn exit)	0.0 m	0.275 m	Active
3	Static Rollover Threshold	0.417 g (R = 100 m) 0.410 g (R = 20 m)	0.416 g (R = 100 m) 0.412 g (R = 20 m)	Active
4	Rearward Amplification	1.202	0.970	Active
5	Yaw Damping Coefficient	0.533	0.487	Active
6	High-Speed Transient Offtracking	0.201 m	0.365 m	Active
7	Horizontal Tyre Forces	Absolute value of pavement wear for baseline vehicle not determined.	Pavement wear due to: *a)* <u>*Horizontal forces*</u> - 160,000 to 190,000 times smaller than baseline vehicle. *b)* <u>*Vertical forces*</u> - 3.2 and 4.3 times smaller than baseline vehicle.	Active

Table 2 – Summary of Performance Levels for Standards Considered (from Prem et al, 2002).

#	Performance Measure	Performance Level (Prem et al, 2002)
1	Low-Speed Offtracking *(maximum swept path width)*	5 m local roads; 7.4 m arterial roads; 10.1 m major freight routes; and 13.7 m road train areas.
2	Tail Swing (turn entry/exit)	0.35 m
3	Static Rollover Threshold	7 0.40 g, dangerous goods and buses 7 0.35 g, all other heavy vehicles
4	Rearward Amplification	$5.7SRT_{rrcu}$ (refer to main text)
5	Yaw Damping Coefficient	7 0.15
6	High-Speed Transient Offtracking	0.8 m
7	Horizontal Tyre Forces	No greater than 1.8 times more damaging than the damage caused the reference vehicle (Austroads design primer mover and semi-trailer).

Table 3 – Summary of Performance Levels for Standards Considered (from Prem et al, 2002).

#	Performance Measure	Trackaxle *cf* Baseline	Trackaxle *cf* Austroads/NRTC
1	Low-speed offtracking	Better	Acceptable for arterials
2a	Tail swing (on entry side of turn)	<u>*Worse*</u>	Standard met
2b	Tail swing (on exit side of turn)	<u>*Worse*</u>	Standard met
3	Static rollover threshold	Similar	Standard met
4	Rearward amplification	Better	Standard met
5	Yaw damping	<u>*Worse*</u>	Standard met
6	High-speed transient offtracking	<u>*Worse*</u>	Standard met
7	Horizontal tyre forces	Better	Standard met

Fig. 1 Rear view of the Trackaxle system showing how the entire axle group is steered relative to the trailer chassis.

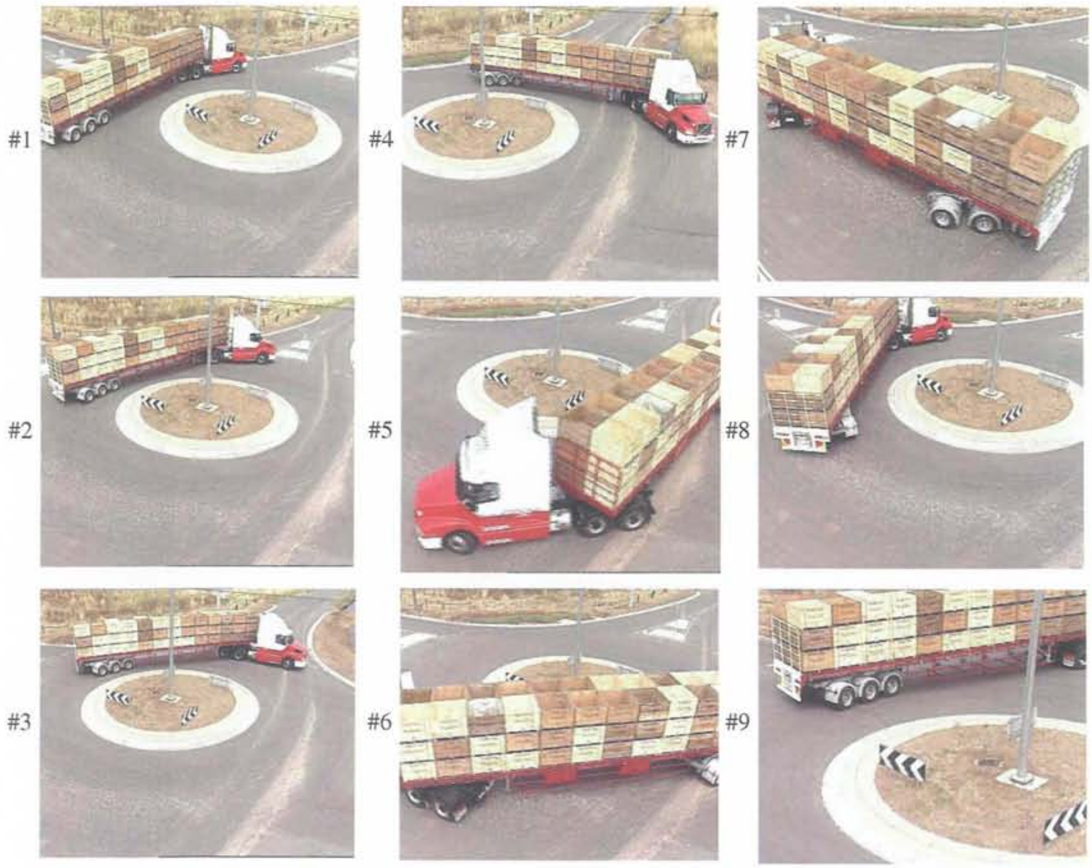

Fig. 2 Illustration of Trackaxle on an urban roundabout (*commence left column, go top to bottom).*

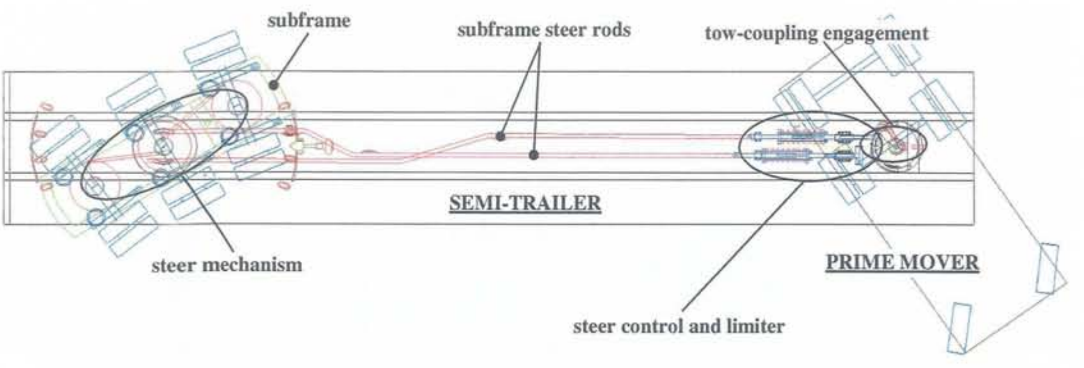

Fig. 3 Schematic showing the main parts of the Trackaxle system.

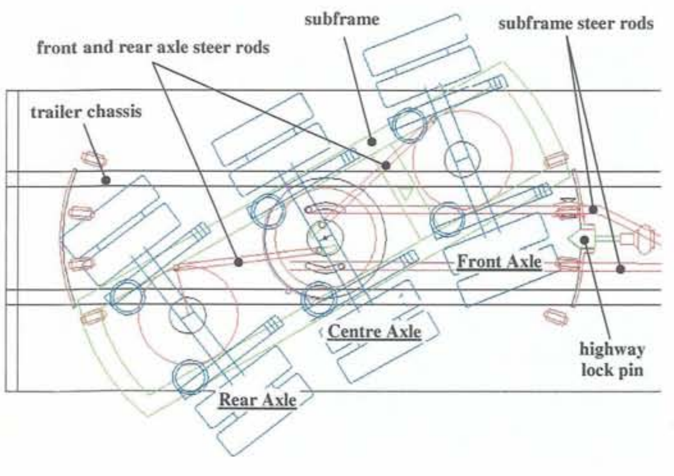

Fig. 4 Schematic showing steer mechanisms between subframe and chassis, and front and rear axles and centre axle (adapted from drawings supplied by Gayat Pty Ltd).

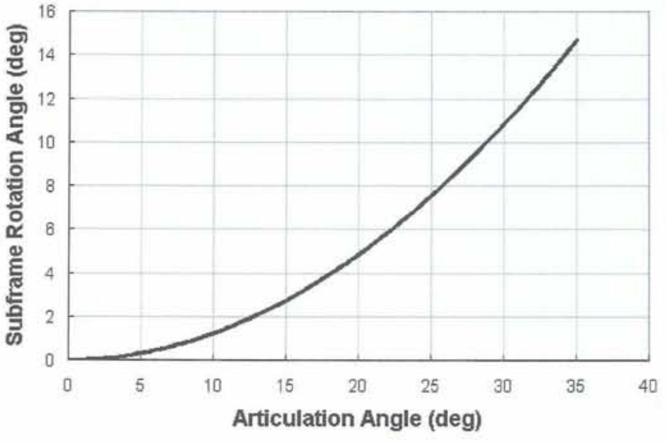

Fig. 5(a) Basic relationship between articulation angle and subframe rotation angle with the steer limiter not active.

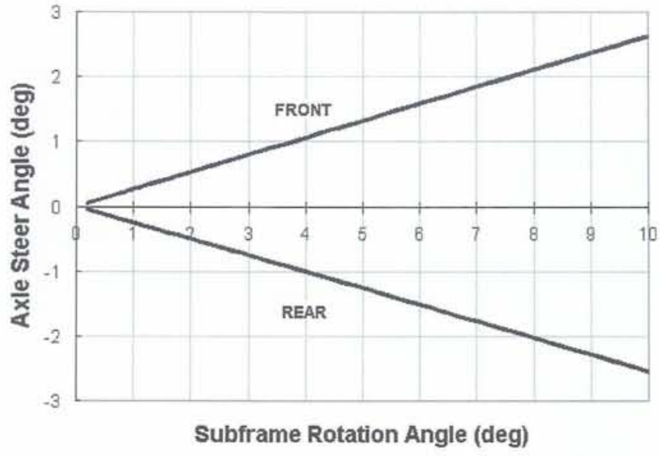

Fig. 5(b) Relationship between subframe rotation angle and the steer angle of the front and rear axles of an axle group.

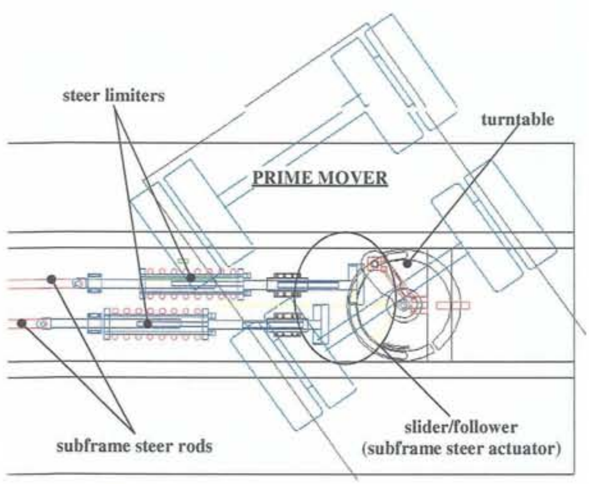

Fig. 6 Schematic showing subframe steer-actuating mechanism and steer limiter spring arrangement.

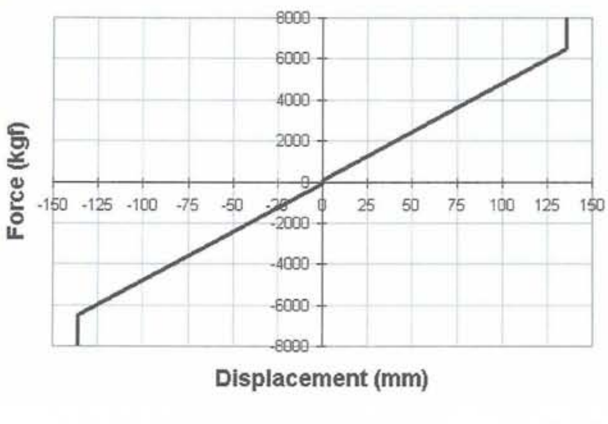

Fig. 7(a) Idealised characteristics of the steer limiter for the full range of spring displacements.

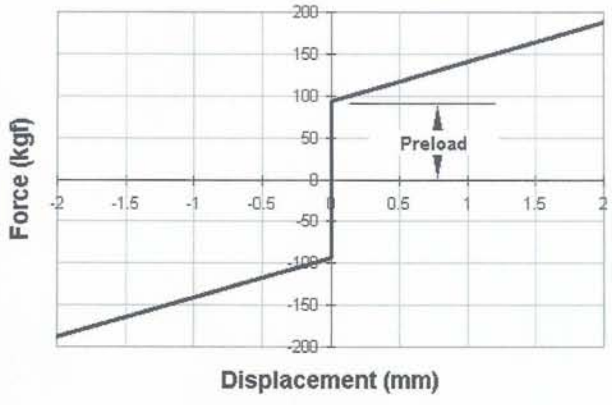

Fig. 7(b) Idealised characteristics of the steer limiter for small displacements showing the effect of spring preload.

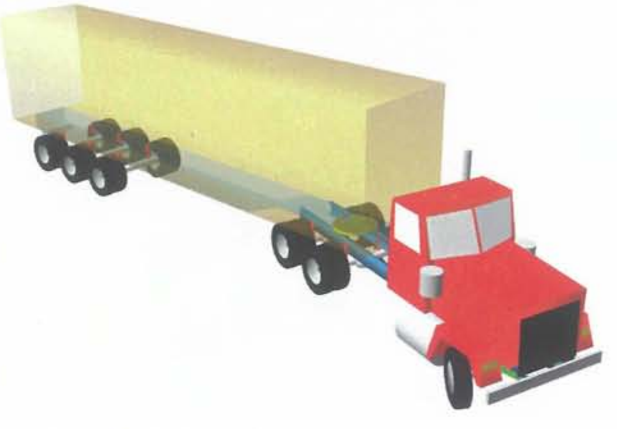

Fig. 8(a) RTDynamics model of the Austroads design prime mover and (13.7m) semi-trailer.

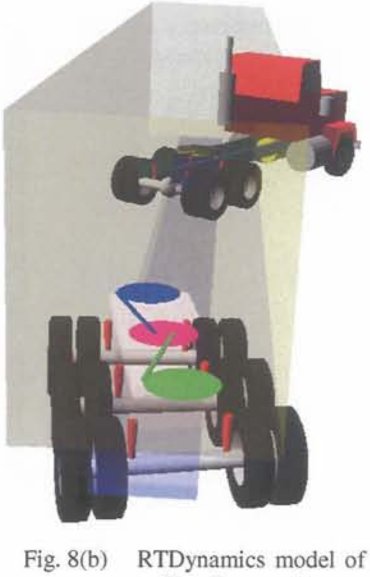

Fig. 8(b) RTDynamics model of the prime mover and the Trackaxle (15.8m) semi-trailer. For consistency the prime mover is the same for both models.

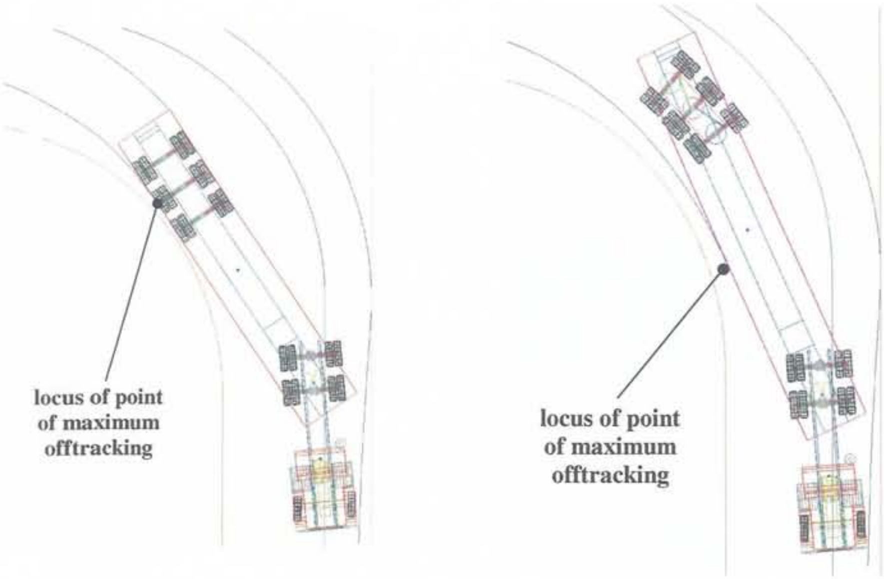

Fig. 9 Location of maximum offtracking for baseline vehicle (left) and Trackaxle (right). On the Trackaxle trailer the point of maximum offtracking is well inside the path of the rear axle group.

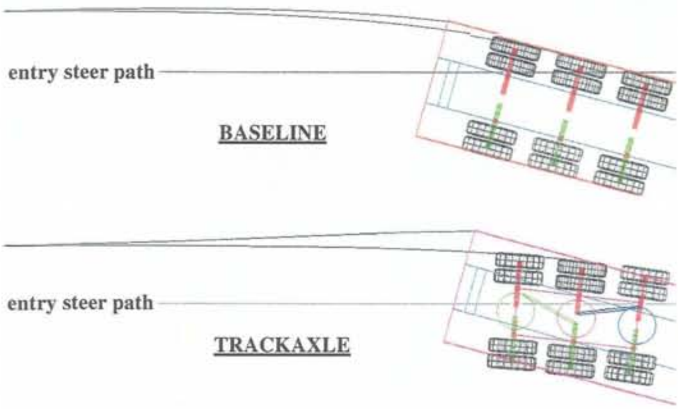

Fig. 10 Trackaxle tail swing compared to baseline during the initial stages of the low-speed turn. (Steer of the front and the rear axles on Trackaxle is evident.)

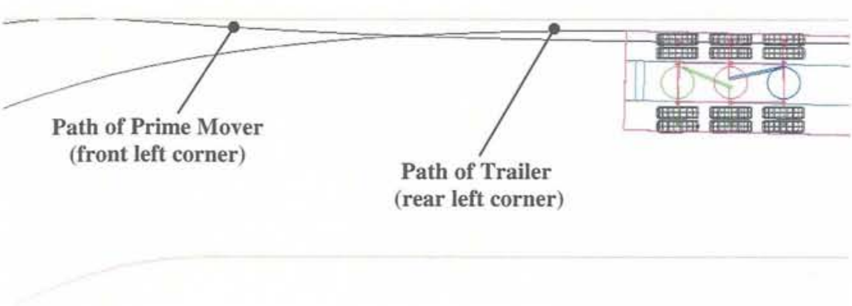

Fig. 11 Trackaxle tail swing (or overshoot) on the exit side of the turn.

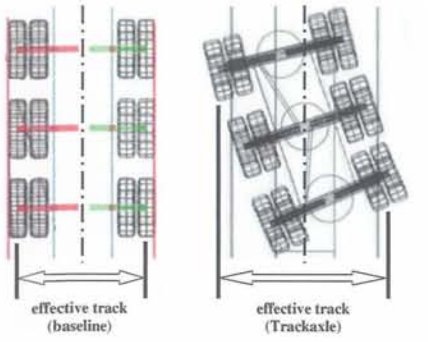

Fig. 12 Effective track for a conventional tri-axle group and Trackaxle, as defined by Gayat (2000a).

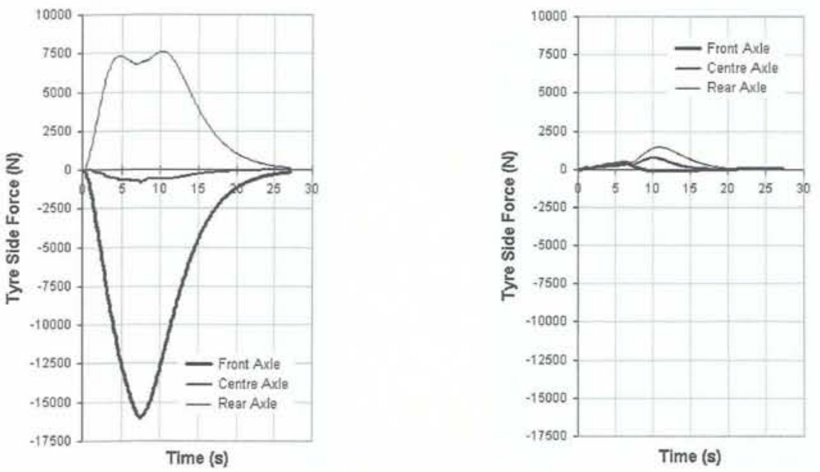

Fig. 13(a) Typical horizontal forces for tyres on the inside of the turn. These show larger forces are imposed on the pavement by the baseline vehicle (plot on the left) compared to Trackaxle (plot on the right).

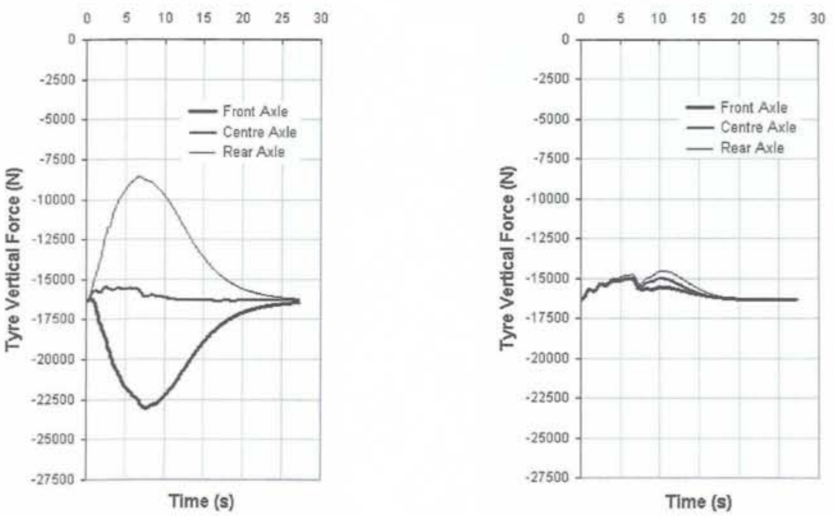

Fig. 13(b) The vertical forces corresponding to those in Fig. 13(a), showing that the horizontal forces modify the vertical forces.