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A NEW STEERABLE WHEEL SYSTEM FOR ROAD TRANSPORT APPLICATIONS



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Abstract
Steerable Wheel Systems Pty Ltd (SWS) in Australia has developed a novel and innovative steerable wheel group system comprising a modular, electronically controlled and integrated steerable wheel-pair and suspension. Formal performance assessments of a number of commodity-specific heavy vehicle design proposals have been carried out under the Performance-Based Standards (PBS) system of heavy vehicle regulation. The design proposals are based on a conventional prime mover towing unit and innovative semi-trailer designs incorporating the SWS steerable wheel group modules. All of the proposal vehicles considered would meet the PBS safety standards at the nominated road class route access levels. Some of the proposal vehicles were estimated to have a static rollover threshold of 0.65g and higher, rearward amplification as low as 0.77, and extremely good low-speed swept path width characteristics, overall exhibiting exceptional levels of safety performance. For the proposal vehicles considered productivity gains were found to be in the range 18 to 32.8%.

Keywords: Heavy vehicle, Steering system, Innovation, Performance-based standards, Numerical modelling, High productivity, Safety performance.

Résumé
Steerable Wheel Systems Pty Ltd (SWS), en Australie, a développé un système de roue directrice novateur, comprenant les suspensions et un essieu directeur intégré contrôlé électroniquement. Une évaluation formelle des performances dans le cadre de l'intégration au poids lourd a été menée en utilisant les normes fondées sur les performances (PBS) édictées par l'autorité réglementant les poids lourds. La proposition de configuration repose sur un tracteur conventionnel auquel une remorque intégrant le système développé par SWS. Les véhicules ainsi testés répondent tous aux critères de sécurité PBS en fonction du type de route. Ainsi, les premières estimations montrent que des véhicules équipés ont des seuils de retournements statiques de 0.65g et plus, une amplification au niveau du train arrière proche de 0.77, ainsi qu'un très bon comportement à basse vitesse pour une grande variété de caractéristiques. Dans l'ensemble, les réponses aux critères de sécurité sont exceptionnelles. Ainsi, les gains de productivité pour les véhicules considérés varient entre 18 et 32.8%.

Mots-clés: Poids lourd, système de direction, innovation, norme fondés sur les performances, modélisation numérique, productivité forte, performance en sécurité.

1. Introduction

Steerable Wheel Systems Pty Ltd (SWS) in Australia has developed a novel and innovative steerable wheel group through its principal Mr Garth Davey. The system, which has local and international patent protection, comprises a modular and essentially "bolt-on", electronically controlled and integrated steerable wheel-pair and suspension. The concept has been successfully demonstrated in a number of heavy haulage applications.

Through a program of research and development the wheel group concept, together with specific hardware, has been further developed and refined for a range of potential heavy vehicle road transport applications. A number of commodity-specific heavy vehicle design proposals have been developed, and numerical modelling has been used to carry out formal performance assessments of those designs under the Performance Based Standards (PBS) system of heavy vehicle regulation that is being developed jointly by the National Transport Commission (NTC) and Austroads in Australia.

This paper briefly describes the steerable wheel group system, the proposal vehicles that were considered and the results of the PBS analysis that was performed, initially considering one specific proposal vehicle for the transportation of quarry product.

2. Background

2.1 Background to Steerable Wheel Group Concept

An early example of an SWS steerable wheel group module is shown below in Figure 1. The wheel group module comprises, in broad terms, an upper load-bearing block that is attached to the main load supporting chassis and steered relative to it, and a hydraulic active suspension system connecting at one end the upper block and at the other end a short axle having a wheel mounted on each end.

Figure 1 – Early example of an SWS steerable wheel group.

By assembling two or more such wheel-group modules side-by-side axles (or rows of wheel-group modules) can be formed. Each row, in turn, can be placed at one or more locations along a load bearing surface or platform to carry a load, as illustrated in the prime mover and semi-trailer combination example shown below in Figure 2.

In a typical application each wheel-pair is steered independently of wheel-pairs in other wheel groups, but as a whole working together in concert in response to an electronic steer signal ("steer-by-wire"). The steer signal is derived from steer algorithms programmed into a central electronic control unit to achieve a desired vehicle response that is consistent with the driver's steering activity, towing vehicle responses, and the prevailing road conditions and traffic.

In its most basic form the steer signal to each wheel group is responsive to the articulation angle between the prime mover and the semi-trailer. Wheel group steering – at individual wheel-pair modules and as a whole – can be controlled and optimised in a way that minimises low-speed swept path, reducing tyre scrubbing forces imposed on pavements to levels that are significantly less than those from conventional axle group arrangements, and less than can be achieved with other current steerable axle systems. Improvements in high-speed performance can also be achieved.

Figure 2 – Early application of the SWS steerable wheel group in a multiple wheel-group (3 per "axle"), multiple-row (6 axles) load platform.

In order to support the load uniformly across and along the length of the load bearing platform, and to achieve good load sharing between wheel groups in order to uniformly distribute loads onto pavements and bridges, the hydraulic, actively controlled suspension on each wheel group has a long stroke and is connected to the other wheel groups by a sophisticated load limiting arrangement.

The wheel group concept has been proven in hardware and successfully demonstrated in a number of specialist heavy haulage road transport and industrial applications. Two examples are a load platform for carrying indivisible loads at speeds of up to 100 km/h and, separately, a low-speed straddle carrier for transporting large metal ingots. These examples are shown below in Figure 3. In each application sideways pointing ultrasonic sensors located on the load platform and carrier are used to automatically and precisely control steering at each wheel group when reversing into tight unloading areas and when positioning the straddle carrier over a load of ingots.

Figure 3 – Two example demonstrators showcasing SWS wheel group technology; a platform trailer (left image) used to transport indivisible loads (a transformer shown) and a straddle carrier (right image) for transport of metal ingots.

2.2 Steer and Load Distribution

The original SWS steerable wheel group (shown in Figure 1) has been further developed and refined. The key features of later generation versions of the wheel group retain the main features of the proven original design with improvements to facilitate mass production, weight reduction, easy installation and maintenance, and general utility in heavy vehicle road transport operations. Some details of the later version of the SWS wheel group are shown in Figure 4. These highlight the long-stroke achieved with the patented "Z-link" hydraulic suspension system and full ±360º digitally controlled steer-rotation capability, which is achieved through the centrally-pivoting ring-gear/worm-drive arrangement located near the top mounting face of the upper block.

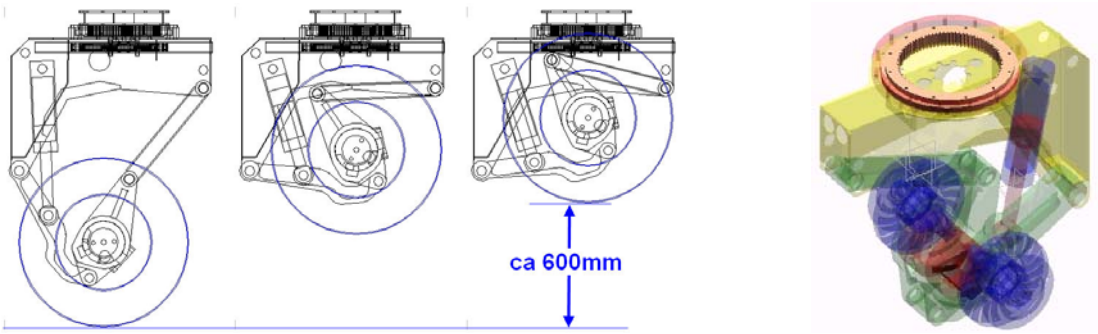

Figure 4 – "Z-link" suspension wheel travel (sequence on left), and numerical 3-D model for motion/wheel-clearance studies and structural analysis (image on right).

In a patented further refinement, each wheel in a wheel pair has its own separate suspension with freedom to move in the vertical (stroke) direction independently of the other wheel (see Figure 5). This new feature is designed to improve load distribution between the wheel pairs within a wheel-pair group, supplementing the existing load limiting arrangement between wheel-pair groups described above. In this way each wheel is both independently sprung and it can load share with each wheel in all the other steerable wheel groups, leading to near-ideal load share capability.

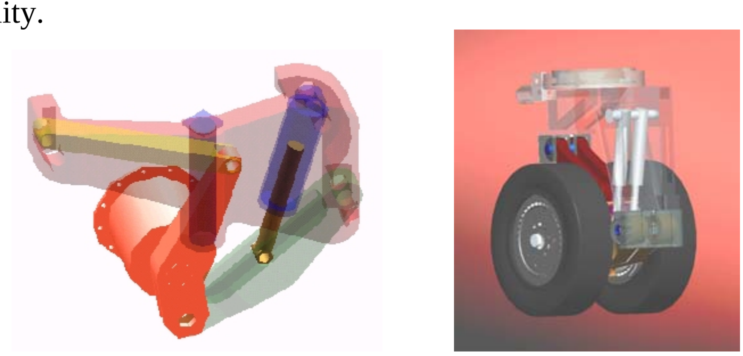

Figure 5 - Left half of latest wheel-pair arrangement (left image) and modular steerable two-wheel assembly (right image)

3. Proposal Vehicles

3.1 Freight Commodities

A range of commodity-specific sectors of the road transport industry was considered for initial application of the steerable wheel group technology. Commodity sectors judged in the appraisal as best suited to the technology were considered in more depth and a final decision was based on the following general selection criteria:

1) Wheel group technology readily applicable/adaptable to transport and handling of commodity at loading/unloading points;

2) Specific industry sector is likely to be receptive to new technology;
3) Large potential productivity benefits with early take-up;
4) Large potential safety benefits with early take-up;
5) Acceptable infrastructure impacts;
6) Suitable for PBS Level 1 (Unrestricted Access/General Access) and/or PBS Level 2 (Significant Freight routes/B-double routes) road class access (a conscious decision was taken early by SWS to exclude road trains at this stage); and
7) Acceptable levels of risk associated with research and development, and later testing of prototype and pre-production vehicles.

Based on the above, industry sectors were selected dealing in the handling and transport of bulk liquid (both hazardous and non-hazardous, petroleum, milk and water), gas (cryogenic), quarry products, grain, and some sectors of general freight.

3.2 Concept Vehicle Key Features

The benefits of the SWS steerable wheel group concept and the associated structural efficiencies that can be realized in freight-specific bodies is largely derived from the ability to position and space the wheel modules uniformly under the load that is being transported. This allows wheel loads to be more evenly and uniformly distributed and, therefore, imposed onto the infrastructure (pavements and bridges), which in turn makes better and more efficient use of the road asset.

The optimum spacing between parallel rows of wheel groups was determined by SWS to be between 2.5 m and 3.0 m. At a spacing of 2.5 m (or greater) between each row of two or more wheel-group pairs, each row would be classified as a single axle fitted with dual tyres. Therefore, a "tri-axle" set of SWS wheel groups operating at full general-mass axle-load limits would support 27 t compared with a standard tri-axle group which is limited to 20 t.

Using this basic approach, a number of concept vehicle layouts were developed. In the main, these comprised a standard single-steer tandem-drive prime mover towing an innovative semi-trailer with a "multiple axle" SWS steerable wheel module arrangement. The quarry transport example shown below in Figure 6 is typical, incorporating a range of features common to all the designs considered, as summarised in the following:

a) *Widely spaced axles and individually steered wheel-pair modules* – Compared with a conventional semi-trailer design the axles are widely spaced and the payload is supported more uniformly along its length. This leads to better distribution of load along bridge spans and on pavements. The individually steered wheel pairs can be precisely controlled minimising tyre scrub (and the associated pavement horizontal tyre forces) at each wheel position in low-speed turns;
b) *Large volumetric capacity* – Unlike conventional semi-trailer designs the load space between the wheel groups is fully utilized, as illustrated below in Figure 7;
c) *Low tare weight* – The wheel group arrangement does away with beam axles, and each wheel group is integrated directly into the body structure eliminating the need for intermediate, load supporting chassis members that distribute point loads;
d) *Low sprung-mass centre-of-gravity (CG) height* – The load space between wheel group pairs is utilised leading to a very-low sprung-mass CG, as illustrated below in Figure 7;
e) *Wide spring-track and long-travel, soft suspensions* – A wide spring track (as illustrated below in Figure 7) and long-stroke soft springs allows high suspension roll stiffness to

be achieved leading to improved rollover stability with less reduction in load sharing capability and more uniform tyre loads;

f) *Electronically controlled wheel-load limiting* – Leads to better support of payloads, better distribution of loads along bridge spans and onto pavements, and elimination of overloading at each wheel position and overall gross mass; and

g) *Axle-lift capability* – Each SWS modular wheel pair has lift capability allowing a row/axle to be raised when operating at reduced GCM. When the vehicle is empty leaving one axle down and raising the others on the semi-trailer reduces general wear and tear on the vehicle and improves driver ride quality. Further, to assist maintenance or change out of wheels or entire wheel modules, individual wheel pairs can be lifted and others pushed down (to raise the semi-trailer).

These design features have significant positive outcomes on vehicle productivity, safety performance, infrastructure impacts and occupational health and safety.

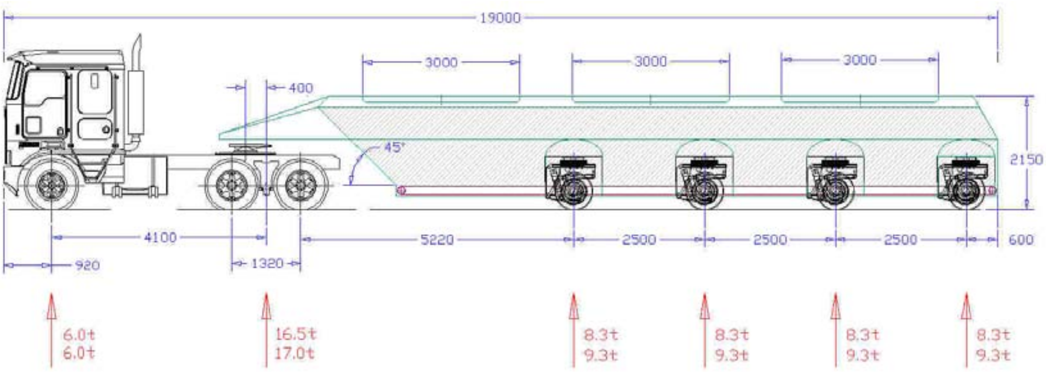

Figure 6 – Example quarry transport that features the steerable wheel module at general and higher mass limit axle group loads, 55.7 t and 60.2 t GCM, respectively, for operation on approved B-double routes

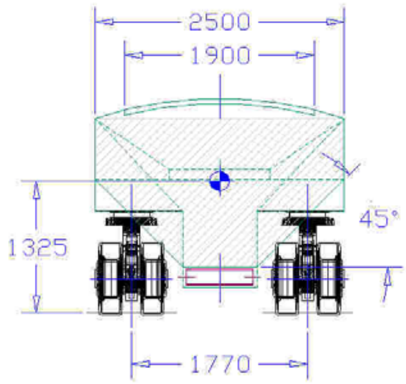

Figure 7 – Rear section view of quarry transport, typical, illustrating additional load space between the wheel modules, low CG and wide spring track.

3.3 Potential Productivity Gains

Indications of potential productivity gains were developed for each concept vehicle and commodity-specific body. These are based on typical tare weights and payloads carried by current conventional vehicles in each of the applications considered, combined with estimates of tare weight and payload of the proposal vehicles. Productivity gain estimates are summarised below in Table 1.

The maximum productivity gains are derived from a comparison of replacing the conventional vehicles with the most appropriate proposal vehicles based on discussions with transport operators. For example, a conventional 6-axle prime mover and semi-trailer road tanker would be replaced by the corresponding proposal 3-axle prime mover and 6 wheel-group semi-trailer road tanker, a tandem-tandem B-double would be replaced by a 3-axle prime mover and an 8 wheel-group semi-trailer combination, etc.

Table 1 – Summary of potential productivity gains.

Commodity	**Conventional**		**Proposal Vehicle**		**Productivity Gain**
	Tare(t)	**Payload(t)**	**Tare (t)**	**Payload(t)**	
Petroleum	14.3 to 18.5	31.2 to 39.6	13.4 to 14.4	36.1 to 45.5	15.6%
Gas	22.0	26.8	24.8	31.0 to 35.6	32.8%
Quarry	15.4 to 23.2	36.1 to 44.8	14.3 to 17.0	35.2 to 45.0	18.0%
Grain	23.5	44.5	17.6	52.6	18.2%

Table 1 shows that productivity gains are predicted to be in the range 15.6% to 32.8%. These represent a significant improvement in productivity over that available with current conventional combinations performing the same freight tasks.

4. Performance Based Standards (PBS)

4.1 Assessment of Infrastructure Impacts

Formal rules for the assessment of infrastructure impacts under PBS are presented in National Transport Commission (2007). The rules for infrastructure assessment are essentially prescriptive in nature, limiting axle vertical loads to those that presently apply under existing prescriptive schemes, and controlling horizontal loading by limiting maximum gross mass in response to the number of driven axles. Similarly, bridge effects are controlled through a series of bridge formulae linked to road network access. These essentially prescriptive requirements were satisfied by the concept vehicles considered.

4.2 Assessment of Safety Performance

The safety performance of the example proposal vehicle considered in this paper was assessed using state-of-the-art numerical modelling and the latest set of nationally accepted PBS heavy vehicle safety standards (National Transport Commission, 2007).

Developed jointly by the National Transport Commission and Austroads, formal rules for assessment of potential PBS vehicles (“the Rules”) have been approved by Ministers (National Transport Commission, 2007). The PBS standards allow the safety performance of each proposal vehicle to be quantified and assessed in absolute terms. The complete set of PBS safety standards were considered in the assessment, however, only a selection of these will be presented in this paper for several of the commodity-specific concept vehicles.

5. Numerical Models

5.1 General Description

For analysis of the safety performance a number of numerical models were created using the ADAMS multi-body dynamics simulation software package (MSC.Software, 2007) and MSD's *Atruck*™ toolbox. For analysis of the longitudinal performance MSD's *GradeSIM*™ software was used. Not all of the proposed vehicles were modelled and tested, instead, only a select number were chosen with the view they would represent best and worst case performances, and thereby cover the range of safety performance of all the design proposals. A general view of the quarry transport numerical model is shown in Figure 8 as an example.

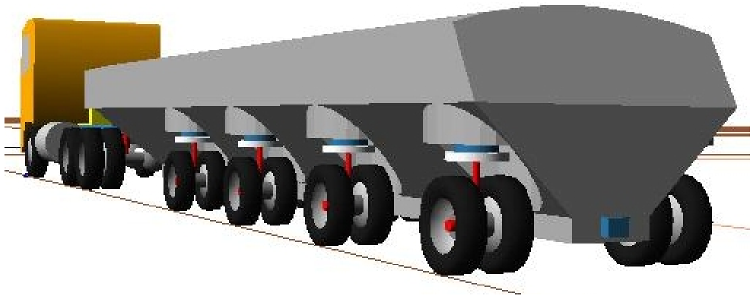

Figure 8 – General view of the numerical model of the 7-axle quarry truck created in ADAMS using MSD's *Atruck*™ toolbox.

5.2 Model Parameters

Mechanical properties were assigned to components (sprung and unsprung masses, suspension, tyres, etc) in each of the models consistent with components on the proposal vehicles. To define datasets for each model, information and performance data were obtained from various sources, including SWS, truck manufacturers, component suppliers (for tyres), a previous major study of the performance of the Australian heavy vehicle fleet (Prem et al, 2002), and, where necessary, drawing from MSD's extensive heavy vehicle database and library. For the analysis best estimates (conservative) of the sprung mass CG heights were used based on individually modelled bodies and associated components.

5.3 Suspensions and Tyres

Suspensions and tyre elements in each of the models were represented as non-linear systems incorporating state-of-the-art features. Where component level test data were supplied (tyres, for example) the component models were adjusted and tuned to accurately reproduce the measured performance characteristics.

Two different tyre sizes were used as advised by SWS. On the prime mover 11R22.5 size tyres were used on the steer and drive axles, on the semi-trailer 235/75R17.5 size tyres were used. Cornering characteristics and load-deflection curves for the 235/75R17.5 size tyres were based on test data obtained from the tyre manufacturer, those for the 11R22.5 size tyres were based on test data used in a previous major study of the performance of the Australian heavy vehicle fleet (Prem et al, 2002).

5.4 Wheel Group Steering

In its simplest form the steer signal to each wheel group is responsive to the articulation angle between the prime mover and the semi-trailer. For a low-speed turn and using a range of steer algorithms this occurs, conceptually, in the manner shown below in Figure 9. The steer algorithm, programmed into an electronic on-board control unit, sets the location of the instantaneous turn centre, a point about which the wheels turn, which can be adjusted automatically during the turn and made responsive to other inputs, such as speed.

At low-speed and tight turns the semi-trailer's instantaneous turn centre closely tracks the instantaneous turn centre of the prime mover, and the two units rotate about points that are in close proximity to each other. If set up correctly, this reduces tyre scrub and minimises swept path width. Figure 9 shows that under low-speed turn conditions the semi-trailer wheels at the rear are steered in a direction that is opposite to the steer of the wheels on the prime mover.

At high-speed the wheels on the semi-trailer are steered in manner which reduces both rearward amplification and the tendency of the trailer to swing out. The direction of steer and the magnitude of the applied steer angle, derived from proprietary algorithms and programmed into the electronic on-board control unit, are sensitive to speed, the severity of the manoeuvre and turn direction.

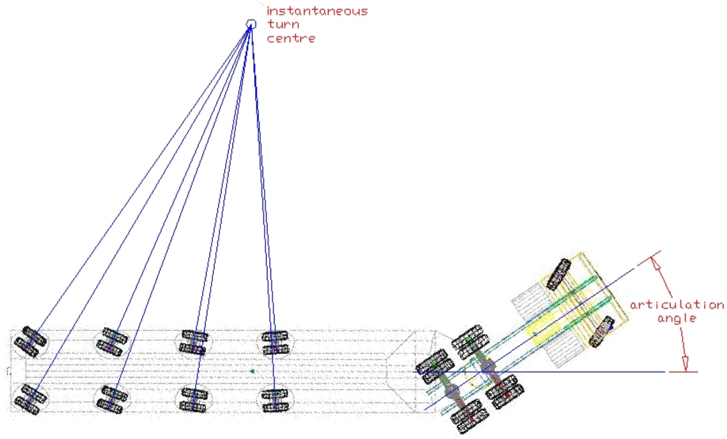

Figure 9 - Illustration of the basic steer relationship between articulation angle and semi-trailer wheel steer in low-speed turn.

6. Results and Discussion

The main results are presented in a series of plots which contrast the performance of the SWS concept vehicles against the performance of the Australian heavy vehicle fleet taken from Prem et al (2002). Only four specific performance measures are presented in this paper.

6.1 Low-Speed Swept Path

The PBS low-speed swept path measure considers the maximum width of the vehicle's swept path in a prescribed 90° low-speed turn. The results for the proposal vehicles are presented in **Figure 10**, which show clearly that the performances compare favourably with the low-speed turn performance of truck/trailer and A-double combinations. Truck/trailer and A-doubles have one and two additional articulation points, respectively, and shorter wheelbase semitrailers than the proposal vehicles. These features of the truck/trailers and A-doubles are known to improve low-speed offtracking but they impact adversely on high-speed dynamics

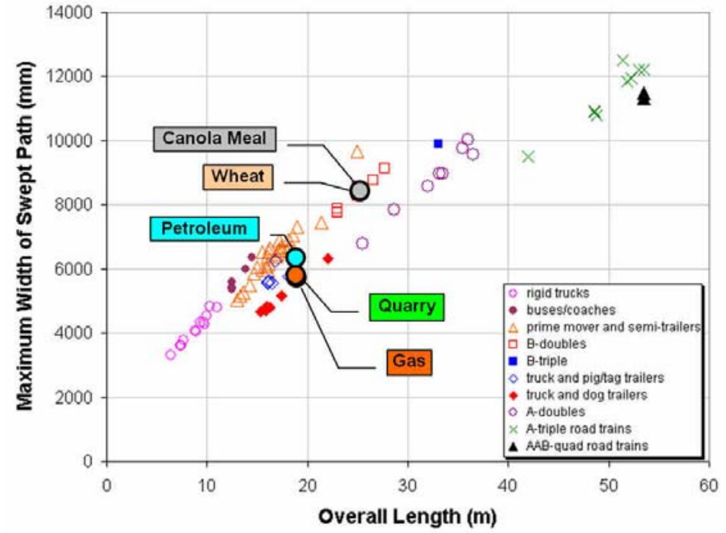

Figure 10 **–** Swept path width performance of the proposal vehicles compared with Australian fleet vehicle performance (from Prem, et al, 2002).

6.2 Static Rollover Threshold

This performance measure considers the steady state level of lateral acceleration during a constant-radius steady-speed turn that the entire vehicle can sustain without rolling over. The static rollover stability performance is compared below in Figure 11 with the performance of the Australian heavy vehicle fleet (from Prem et al, 2002), highlighting the outstanding results achieved with the low CG proposal vehicle designs.

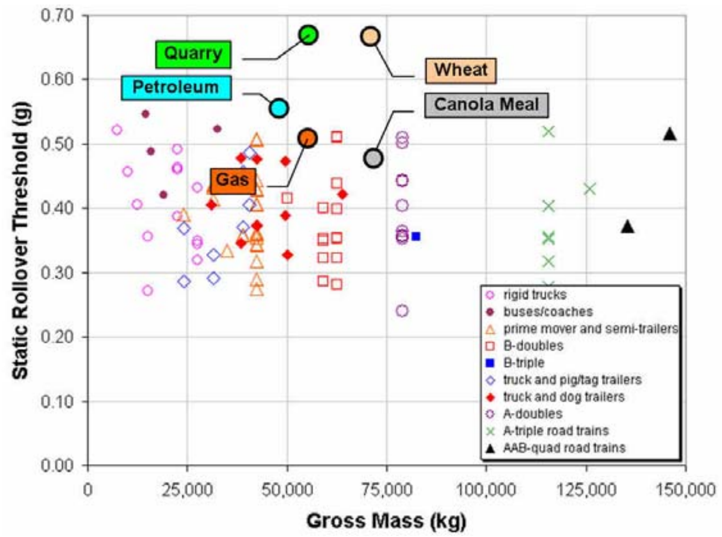

Figure 11 – Static rollover threshold performance of the proposal vehicles compared with Australian fleet vehicle performance (from Prem, et al, 2002).

The safety implications of the improvements in rollover stability is made more apparent and further reinforced by referring to Figure 12 below, which shows there is a very clear relationship between crash involvement and static rollover threshold; the higher the static rollover threshold the lower the involvement. This finding, first reported in a major crash study in the USA (Ervin et al, 1986), is supported by a later study in New Zealand conducted by Mueller, de Pont and Baas (1999). They found that 15% of vehicles in the fleet had a static rollover threshold value below 0.35g but were involved in 40% of the stability-related crashes; vehicles with a static rollover threshold of 0.3g or less had more than 3 times the crash rate of the rest of the fleet.

The safety benefits of the SWS wheel group are apparent, and Figure 12 suggests the number of single-vehicle rollover crashes could be significantly reduced if the static rollover threshold profile of the fleet, or specific fleet sector could be improved.

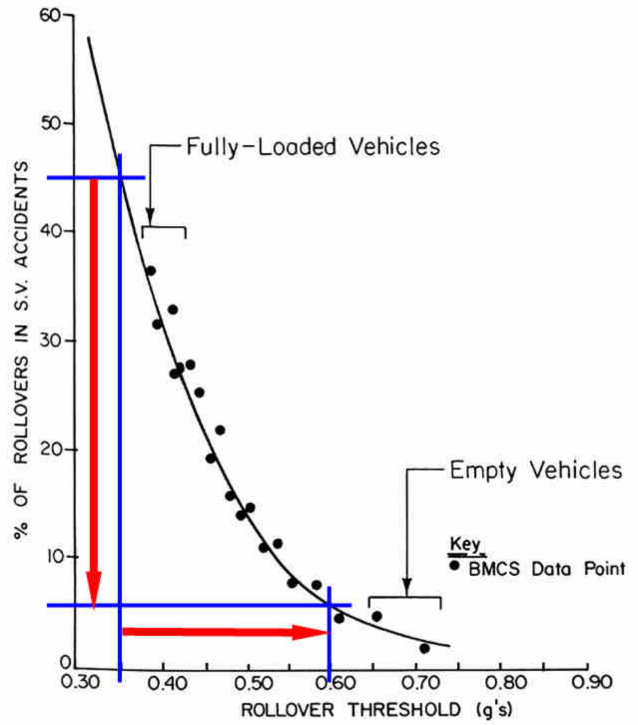

Figure 12 – Percent of single-vehicle accidents in which rollover occurs shown as a function of the static rollover threshold (adapted from Ervin et at, 1986).

6.3 Rearward Amplification

Rearward amplification measures the degree to which the trailers in a combination amplify the lateral acceleration of the prime mover in a prescribed lane change manoeuvre. Rearward amplification for the proposal vehicles is compared below in Figure 13 highlighting the outstanding results achieved with the now combined effects of the low CG design and the high-speed steer strategy. In particular, it is important to note that for two of the five proposal-vehicles rearward amplification is equal to unity (quarry and cryogenic) and for the remaining three, petroleum and grain (wheat and canola), rearward amplification is less than unity, 0.95, 0.77 and 0.86, respectively. In the case of the three with rearward amplification values less than unity the term "rearward attenuation" would be more appropriate.

6.4 High-Speed Transient Offtracking

High-speed transient offtracking measures the maximum lateral distance, or sideways distance, that the last-axle on the rearmost trailer tracks outside the path of the steer axle in a prescribed lane change manoeuvre. The high-speed transient off-tracking results are presented in Figure 14, which further serve to highlight the improvement in performance that can be achieved with SWS steerable wheel group technology.

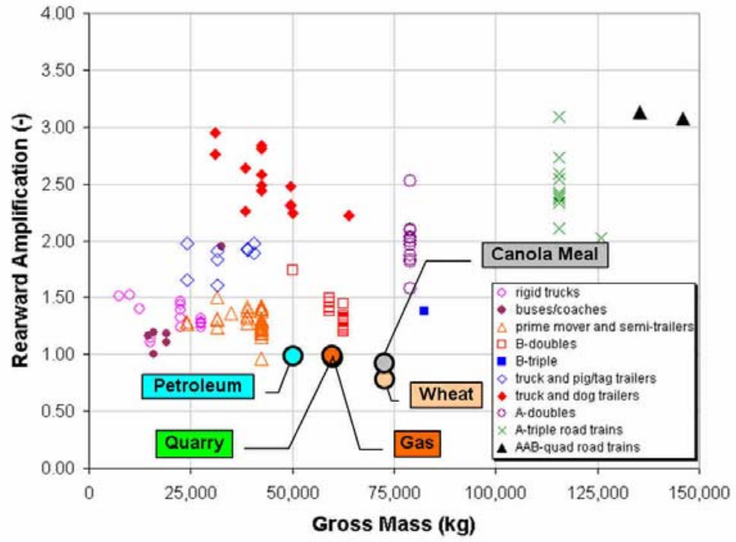

Figure 13 – Rearward amplification performance of the proposal vehicles compared with Australian fleet vehicle performance (from Prem, et al, 2002).

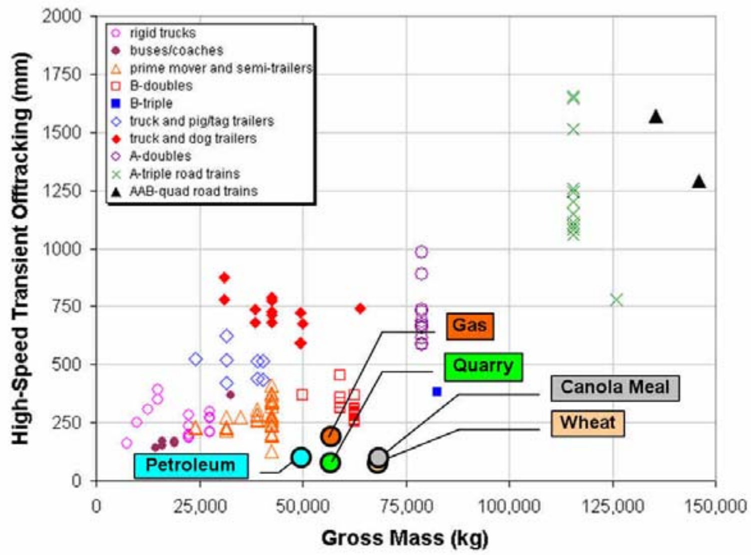

Figure 14 – High-speed transient offtracking performance of the proposal vehicles compared with Australian fleet vehicle performance (from Prem et al, 2002).

7. Concluding Comments

A recent formal PBS assessment and review was conducted in Australia of the 19 m long prime mover and semi-trailer combination, with four independent widely spaced, SWS steerable axles for transporting quarry product, which has confirmed the vehicle meets the PBS safety performance standards. However, the assessment has revealed some shortcomings in the PBS system and its ability to adequately address non-standard configured vehicles such as the ones presented in this paper. NTC intends to further develop the current PBS standards to be able to address innovative vehicles in the future.

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