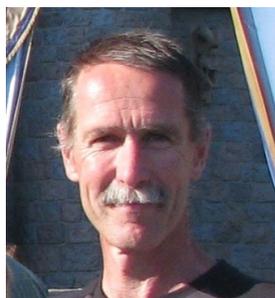# INVESTIGATION INTO THE HIGH-SPEED OFFTRACKING CHARACTERISTICS OF QUAD-AXLE SEMI-TRAILERS WITH ONE OR TWO REAR SELF-STEERING AXLES AND A REVIEW OF THE HIGH SPEED OFFTRACKING PERFORMANCE STANDARD

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Abstract

The high-speed offtracking performance of quad-axle semi-trailers with one or two rear self-steering axles in the quad group was determined through field trials and computer simulations. The outboard offtracking of trailers employing two rear self-steer axles with moderate levels of centring force was found to be highly non-linear with respect to lateral acceleration. This was only evident at lateral accelerations above 0.2 g but below the rollover threshold. Even the poorest performing trailers – quad groups with two rear self-steer axles and moderate levels of centring force passed the Roads and Transportation Association of Canada (RTAC) high-speed offtracking performance measure. A revised high-speed offtracking methodology was developed that took into account differences in road design and the likelihood of heavy combination vehicles exceeding 0.2 g lateral acceleration. The reference values were set so as to fail vehicles with a highly non-linear offtracking response above 0.2 g. As a result it is proposed that a quad-axle semi-trailer will have a prescribed mass limit based on the type of steer axle fitted.

1   Introduction

In 2002, transport legislation regarding mass and dimension limits in New Zealand was amalgamated from various pieces of legislation into Land Transport Rule - Vehicle Dimensions and Mass (VDAM Rule). At that time, following a review process, the maximum number of axles allowed on a semi-trailer was increased from three to four. Under the VDAM Rule, quad-axle sets were required to have two self-steering axles to limit tyre scuffing. The steer axle locations could be either axles one and four or axles three and four. Axle set spacing requirements and the defined location of the rear axis has meant that the majority of quad-axle semi-trailers have self-steering axles fitted in positions three and four (2+2), see Figure 1.
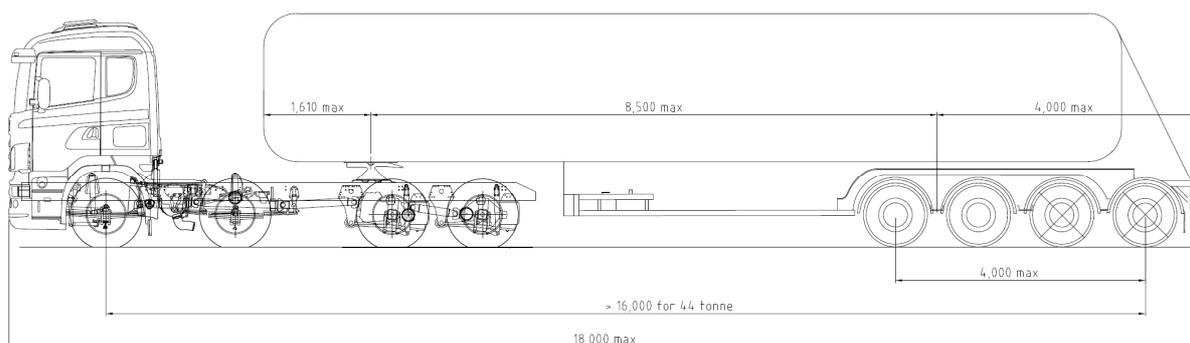

Figure 1: 8x4 tractor unit and quad-axle semi-trailer with two rear self-steering axles

The decision to allow quad-axle sets in semi-trailers was to incentivise the use of tractor semi-trailer combinations in New Zealand and improve productivity in the road freight sector. Since July 2002 more than eight hundred quad-axle semi-trailers have been put into service. During this time, concerns have been raised over the safety performance and road space usage of this type of semi-trailer (Prem and Mai 2006) and (Latto 2009). The safety concerns for the most part have related to the amount of outboard offtracking that the semi-trailer exhibits relative to the path taken by the tractor unit at moderate to high-speed corners. There have also been instances where excessive inboard offtracking has been reported on low speed banked corners (Latto 2009).

The high-speed offtracking performance of quad-axle semi-trailers with two rear steering axles was not extensively tested before their introduction. Field tests were conducted on a quad-axle semi with three fixed and one rear steering axle (3+1), a configuration proposed in a draft of the VDAM Rule (Latto and Bass 2002). Detailed low speed tests were conducted; high-speed tests were limited to observation of on highway operation. The rationale for only conducting limited high-speed testing was that tri-axle semi-trailers with a single rear self-steer axle (2+1) had previously been extensively tested at up to seven tonnes per axle, and it was considered that the 3+1 quad at a maximum of six tonnes per axle would have better dynamic performance than the 2+1 tri-axle configuration.

The decision to change the requirement for the quad-axle set to have two self-steering axles instead of one was made because of the concerns of road controlling authorities about tyre scuffing damage to the road. The proximity of this change to the signing of the VDAM Rule was such that appropriate field testing on the 2+2 combination was not conducted.

The aim of this paper is to report on the results of high-speed offtracking tests of quad-axle semi-trailers and of the development of a high-speed offtracking measure adapted to a roading environment with different topography and design criteria to that where the original measure was developed (Canada).

2   Background

2.1   Semi-trailers with self-steer axles in New Zealand – History and Previous Studies

Semi-trailers fitted with self-steer axles have been used in New Zealand since the late 1960's. At that time, and up until the early 1990's, there were no performance requirements or configuration limitations for the use of self-steer axles in semi-trailers. Legally, the use of self-steering or castoring axles was first permitted in June 1970 (Ministry of Transport 1970). This gave rise to some unique combinations (tri-axle semi-trailers with self-steer axles in positions one and three) and tracking performance issues at speed.

During the early 1990's, the Ministry of Transport (MOT) developed and released a policy statement (Ministry of Transport 1996) regarding the use of self-steer axles in semi-trailers. This was done to address the performance issues raised and, ultimately, allow operations to increase from 37 to 39 tonne gross combination mass (GCM). Under this policy, tri-axle semi-trailers were permitted to have a single rear self-steering axle. Performance requirements for tri-axle semi-trailers fitted with a self-steer axle were contained in this policy statement. Stability analysis by computer simulation was required to determine the High-speed Transient Offtracking (HSTO) which, under the policy, had to be less than 0.6 metres. A physical straight line braking test with a significant brake imbalance across the self-steering axle was also required.

The HSTO requirement had the effect of limiting the maximum permitted vehicle operating mass with a particular brand of self-steering axle. Operation at the then maximum limit of 39 tonne resulted in detailed specification of the minimum centring force requirements for a self-steering axle (White 1990), (McDougall 1990) and (White 1993). The MOT Steerable Rear Axles policy was withdrawn with the introduction of the VDAM Rule in 2002. However, the performance requirements in the policy statement were not carried over into the new Rule. This removed the detailed specification, testing and approval requirements for self-steering axles.

2.2   Semi-trailers with self-steer axles – International Studies

To date only a limited number of detailed investigations into the stability and handling performance of semi-trailers with self-steering axles have been reported on. In the 1980's, the use of self-steering axles as a belly axle in a semi-trailer and in the 'C-dolly' of a C-train was investigated as part of the RTAC weights and dimensions study (Ervin and Guy 1986). The belly axle fitted in the semi-trailer was found to have little effect on the yaw response and the high-speed tracking performance of the combination. This is due to the self-steer axle being positioned close to the trailer centre of gravity and therefore, only having a small lever arm for imposing dynamic moments which could influence the yaw response of the trailer (Billing and Patten 2003). Field testing of a B-dolly combination in which the dolly axle was self-steering (turntable steer) exhibited outboard offtracking in excess of 3.5 metres at the point of rollover and an oscillatory yaw response. The measured lateral acceleration at this point was 0.4 g (Ervin and Guy 1986). Simulations of a B-dolly combination with an air pressure centring type self-steering axle with low centring force exhibited similar offtracking and yaw responses to the B-dolly combination (Ervin and Guy 1986). The RTAC weights and dimensions study proposed and used a number of vehicle performance measures that were used to rank the stability, handling, dynamic response and road space usage of different vehicle combinations. These performance measures have subsequently formed the basis of the vehicle related measures in the Australian Performance Based Standards (PBS) legislation (National Transport Commission 2008).

In 1989, as a result of the issues raised in the RTAC study relating to the use of self-steering axles in semi-trailers and C-dolly's, LeBlanc (1989) further investigated the effect of self-steer axles on steady state handling and brake steer. This study further highlighted the effect that the cornering force properties and location of the self-steering axle have on vehicle handling and performance. The authors concluded that: "1.) self-steering axles should be evaluated in terms of their cornering (cornering/centring force) and brake steer performance and 2.) Since the effect of self-steering axles is highly dependent on the vehicle configuration and on the actual location where the axle is installed, it is imperative that some form of stability and control analysis be conducted to establish the minimum cornering force requirements".

Also in 1989, Winkler (1989) published the results of a study into the influence of rear-mounted, caster-steered axles on the yaw performance of straight trucks and tractor semi-trailer combinations. The effect of self-steer axles that were freely castoring and axles that had a centering force mechanism were included in the investigation. It was found that self-steer axles that had no centering force mechanism were 'categorically undesirable' with regard to vehicle control and stability. Self-steer axles with centring force mechanisms were found to improve vehicle control up until the lateral acceleration required to initiate steering, after which vehicle control and stability was degraded similarly to the freely castoring axle. This analysis also highlighted that high-speed offtracking is markedly affected by the addition of a rear mounted steer axle while only having a small effect on transient high-speed offtracking.

In 2002 a computer simulation based study of the performance of semi-trailer steering systems was conducted by the Transportation Research Group at the University of Cambridge (Jujnovich and Cebon 2002). For this study a new computer simulation program based on the Yaw/roll model developed by the University of Michigan's Transport Research Institute (UMTRI) (Gillespie 1982) was used. The study examined three types of semi-trailer steering systems/axles and compared the stability and tracking performance of each system against a standard tri-axle semi-trailer. Self-steer, command steer and pivotal bogie steering systems were examined and the comparison made with the standard tri-axle semi-trailer by using the performance measures proposed in a draft of the Australian PBS legislation (Prem, Ramsay et al. 2001). This included both low and high-speed tracking measures, handling performance and stability measures. This study only included one type of self-steering axle, namely one that uses a preloaded spring and damper attached to the axle track rod and reacted against the axle beam. With this type of self-steering axle the centring force is not load dependant. The HSO for the combination with a self-steering axle was found to be 0.6 m, 70 mm greater than the standard tri-axle semi-trailer. Both had HSO greater than the proposed 0.5 m limit in the Australian PBS legislation. The simulations were conducted with an axle group load of 24 tonne (8 tonne per axle). The authors of this

study concluded that HSO performance, although over the 0.5 m limit, was acceptable. Notably, it was found that the handling performance of the self-steering axle combination, although passing the 'three point' PBS criteria was vastly poorer than the other combinations, with the understeer gradient reaching the critical level well before the vehicle reached the rollover limit. It was found to not only become directionally unstable, but did so long before the other tested combinations. This lead the authors to conclude that the 'three point' PBS measure did not describe the vehicle handling adequately and recommended looking at the complete handling diagram. The HSO handling performance measure was not included in the finalised Australian PBS legislation, and the handling performance measure is still in draft format (National Transport Commission 2008). The computer simulation model developed for the Cambridge study was subsequently validated by field trails and reported by Jujnovich (2004).

The use of self-steering axles in four, five and six axle semi-trailers was investigated by Billing and Patten (2003) using a modified version of the UMTRI Yaw/roll model. This work was conducted for the Ontario Ministry of Transportation. Semi-trailer configurations with either three or four fixed and one or two self-steer axles were assessed. In the five and six axle semi-trailer combinations, the self-steer axles were either both located ahead of the fixed axles in the 'belly' of the trailer, or one ahead and one behind the fixed axles. In the four axle semi-trailer, the self-steer axle was located ahead of the three fixed axles. Subsequent field trials on a five axle semi-trailer configuration were conducted to validate the earlier findings (Billing and Patten 2004). The steer axles simulated in the computer modelling, and used in the subsequent field trials, utilised an air pressure centring mechanism (Billing and Patten 2004). Billings noted from previous research that: "It is known that the dynamic performance of vehicles with one self-steering axle in the belly position is not significantly affected by the steer-characteristics of the self-steering axle". Furthermore, "It is known that vehicles with a self-steering axle as the rearmost axle may be prone to lateral/directional instability, which could result in a single unit vehicle spinning out, or a semi-trailer swinging across the road" (Billing and Patten 2003 - page 13). Billings considered that while it might "be possible to configure a semi-trailer combination with a rear mounted self-steer axle to meet the normal dynamic performance standards, which attempt to keep the vehicle upright and within its space on the highway at lateral accelerations in the range of 0.15-0.2 g, a more aggressive manoeuvre could still result in a type of crash that would not occur in a vehicle with rigid axles". Billings therefore felt it was necessary to assess the modes of instability of the proposed vehicles under more aggressive manoeuvres, in the range 0.25 to 0.3 g, just below the rollover threshold of such a vehicle carrying a payload with a high centre of gravity. Two additional performance measures, based on a more severe lane change manoeuvre were proposed and used in the study, this evaluated load transfer and transient offtracking at 0.3 g. HSO was not determined in a higher lateral acceleration manoeuvre.

3   High-speed Offtracking – Performance Measure

The literature review on semi-trailers fitted with self-steering axles highlighted the potential for degradation in the handling performance of the combination and increased HSO when the self-steer axle is used in the rearmost position. It also highlighted that semi-trailers with a rear steer axle tend to become "sluggish" in relatively high frequency manoeuvres, such as in a lane change (Winkler 1989), and hence assessment of HSO would be more relevant to categorising the performance of this kind of vehicle than assessing HSTO. HSO was not assessed when investigating the performance of tri-axle semi-trailers with a rear steer axle in the development of the MOT steerable axle policy and only the Rearward Amplification (RA), Load Transfer Ratio (LTR) and HSTO of the 2+2 quad was investigated before the introduction of this combination (Milliken and Mueller 2002).

The HSO measure used in the RTAC study was conceived by the authors because of their involvement in investigating rollover crashes at highway interchanges; in a number of the crashes the HSO phenomenon was found to be a causative factor (Ervin, Barnes et al. 1985). In one particular crash involving a tractor semi-trailer hauling anhydrous ammonia minor HSO of the semi-trailer axles produced a curb strike which precipitated rollover and cargo loss that resulted in the deaths of seven people and injury treatment of 178 others (National Transportation Safety Board 1977). It was the view of the author of the RTAC study that "high-speed offtracking is patently undesirable and that attention should be given to minimising it, wherever practicable" (Ervin and Guy 1986).

The HSO reference value of 0.46 m was identified as providing a minimal clearance of 0.15 m to the outside of a 3.66 m wide conventional traffic lane if a 2.44 m wide tractor followed a path down the centreline of the lane. Billing and Patten used this reference value in assessing four, five and six axle semi-trailers fitted with self-steering axles (Billing and Patten 2004), they noted that although the design lane width in Canada had not changed since the RTAC study, the width of semi-trailers had increased from 2.44 m to 2.59 m. Using the same reference value then meant that the clearance between the rearmost axle and the lane edge was now 0.08 m. Billing and Patten concluded that, with the conservatism built into the HSO performance measure, the way the vehicle combinations analysed are operated and the road design parameters used in Canada, there is a low probability of HSO contributing to crashes on main highways. In Canada the design speed for main highways is 110 to 130 km/h, the truck speed limit is 100 km/h and side friction factors (SFF) are limited to a maximum of 0.16. Hence it was concluded that these combinations were unlikely to experience cornering manoeuvres on highway exceeding 0.2 g lateral acceleration (Billing and Patten 2008). Canadian rural roads and main highways usually have a continuous paved or compacted gravel shoulder 2 to 3 m wide and there will be a barrier if a ditch or cliff is less than 3 m off the paved road or if there is no shoulder (Billing 2010).

Figure 2 plots SFF[1] against design speed as used in North America and New Zealand. This highlights that all curve design speeds in North America have SFF less than 0.2. In New Zealand, all curves with design speeds 75 km/h and below have a SFF at 0.2 or higher. This would indicate that the use of a HSO measure in New Zealand is warranted. Further, studies of heavy vehicle speeds through advisory speed posted curves has shown that heavy vehicle combinations travelled through, on average, 11% faster than the posted advisory speed (de Pont, Charlton et al. 2004). This reduced to 6% above the posted advisory speed for what can be considered high centre of gravity vehicles (laden logging trucks etc.). Measurements of lateral acceleration events above 0.22 g were recorded on a line haul tractor semi-trailer combination over a distance 146,000 to 176,000 km, analysis of the recorded data revealed 352 valid high-speed cornering events with peak lateral accelerations above 0.22 g. This equates to one event above 0.22 g every 414 to 500 km (de Pont, Charlton et al. 2004).
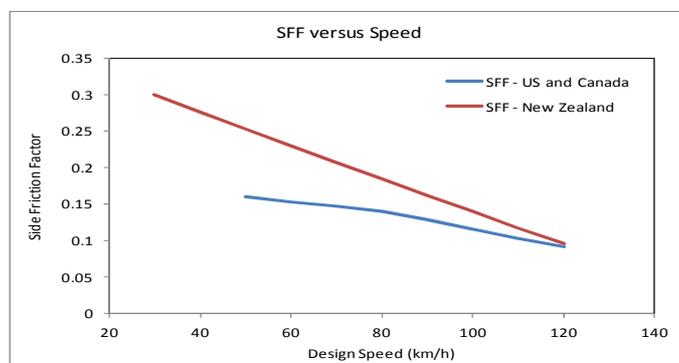
Figure 2: Design Side Friction Factor versus Speed – North America and New Zealand

New Zealand does not have a formal reference value for HSO (de Pont 2011). Some studies have used a reference value of 0.8 m and a test speed of 90 km/h - equating to a lateral acceleration of only 0.16 g. This differs from the original RTAC specification. Setting an HSO limit for New Zealand should reflect not just the difference in lane and vehicle widths, but also the greater relative risk associated with exceeding 0.2 g and greater likelihood of running off the road (Billing 2010).

Using a lane width of 3.5 m, a vehicle width of 2.5 m and a edge of vehicle to lane edge distance of 0.15 m, as used in the RTAC study, yields an HSO limit of 0.35 m. Using a vehicle to lane edge distance of 0.08 m, as used in the later Canadian study of four, five and six axle semi-trailers, would give an HSO limit of 0.42 m under New Zealand conditions. Figure 3 plots offtracking against lateral acceleration for a tractor semi-trailer and doubles combination reported on in the RTAC study (Ervin and Guy 1986). This data shows a linear relationship between offtracking and lateral acceleration up to

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[1] SFF is equivalent to the unbalanced lateral acceleration of a vehicle driving in a curve

0.35 g for the tractor semi-trailer combination and 0.25 g for the doubles combination. The gradient of the offtracking versus lateral acceleration line has been termed the high-speed gradient.
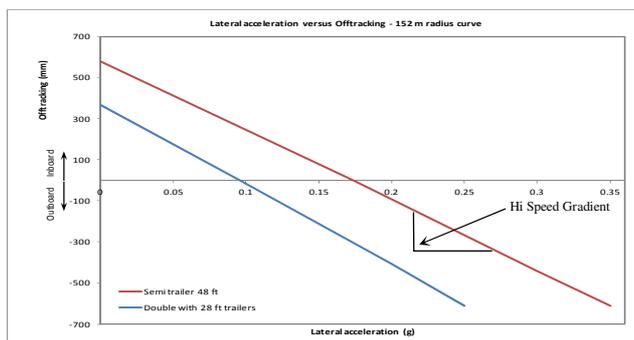

Figure 3: Offtracking - tractor semi-trailer and double combination - 152 m radius curve, source (Ervin and Guy 1986 - p.33)

4   Method

Two quad-axle semi-trailers were selected for field trials. Both trailers had commercially available and commonly specified self-steer axles. These axles were of a leading kingpin automotive steer type, where return to centre performance is achieved through the mechanical trail and an additional centring force mechanism. The centring force mechanisms on both axle types proportion the centring force in relation to axle load. One type produced low to moderate centring force, the rate of which, although axle load dependant, cannot be varied. This is achieved by the use of undulated washers mounted around the kingpin. The second self-steer axle type incorporates a transversely mounted air spring (torpress) to generate an axle load dependant centring force. This is achieved by sensing the air suspension pressure. For a given axle load the air pressure can be varied by adjustment of an air valve – the setting used was typical of in-service use and produced a high centring force. In the results below the trailers using these axle types are referred to as undulating washer centring (UWC) and air pressure centring (APC).

The trailers were fitted with data acquisition equipment and outriggers to prevent rollover. Both trailers had locking mechanisms on their steering axles for reversing. These locks were engaged on the third axles to convert the 2+2 trailers to 3+1 trailers during testing.

The trailers were loaded and tested through two 90 degree curves of 35 and 105 m radii. HSO was measured using spray markers fitted to the centre of the front and rear axles of the combination vehicles. The field test results were compared with the results obtained from computer simulations using the Yaw/roll model. Representative geometric and component data inputs were used to represent the tested combinations on 35 and 105 m radii curves. Further simulations were conducted using the standard RTAC HSO assessment methodology (i.e. 393 m radius at 100 km/h), higher speed simulations were also included to produce lateral accelerations up to 0.3 g.

5   Results

5.1   Field tests

Figure 4 and Figure 5 plot offtracking against lateral acceleration in tests of two quad-axle semi-trailer combinations on the 35 and 105 m radii curves. The tests were conducted at speeds from creep speed up to the rollover limit of the combination. Positive values listed in the tables indicate inboard offtracking, with negative values indicating outboard offtracking.
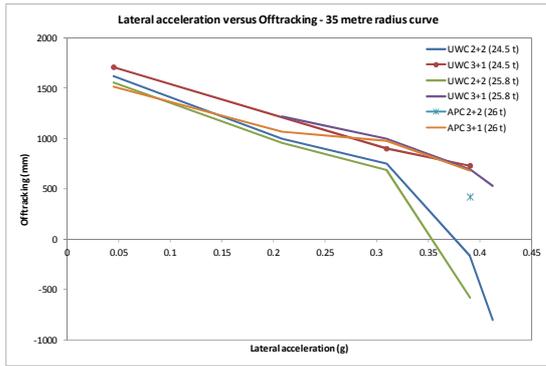
Figure 4: Offtracking versus lateral acceleration – 35 metre radius curve
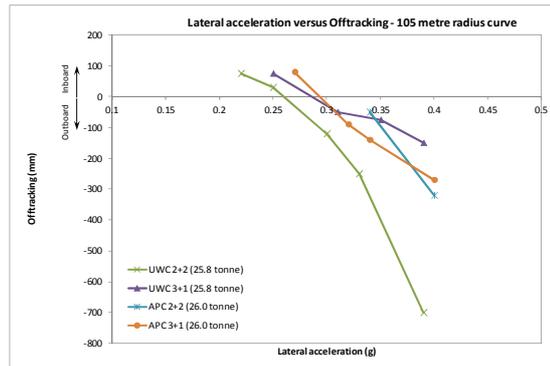
Figure 5: Offtracking versus lateral acceleration – 105 metre radius curve

Figure 6 was taken from the video of a 64 km/h test with the 2+2 UWC combination on the 105 m radius curve, with the degree of steer on the two self-steering axles being visible. It should also be noted that the outrigger has not touched down, at this point, indicating that the combination is still below its rollover limit. Figure 8 plots the steer angle of axle 1 on the tractor and resultant steer angle of axles 3 and 4 on the quad-axle trailer for this test. This shows that axle three steered a maximum of 4.4 degrees and axle four a maximum of 6.2 degrees through the central portion of the curve. The tractor steer input was approximately 2.5 degrees. Figure 10 plots the steer angle data for the 3+1 combination at the same speed. The peak lateral acceleration, tractor axle 1 steer angle and quad-axle 3 and 4 steer angles are listed in Table 1 for the UWC and APC combinations configured as both 2+2 and 3+1 combinations. This data shows that the maximum steer angle of axle 4 on the UWC 3+1 quad group is half that of the 2+2 configuration. A steer angle of up to 0.7 degrees was recorded at axle 3 of the quad group when the axle steering was locked using the reverse lock mechanism. For the APC combination, the 'locked' third axle steers up to 1.5 degrees, which is only 0.4 degrees less than when the axle was free to steer. The degree to which the locked axles steered indicates the level of free play and compliance in the locking mechanism.

Figure 6: Steer angle on axles 3 and 4, UWC – 105 m radius – 64 km/h – 26 tonne
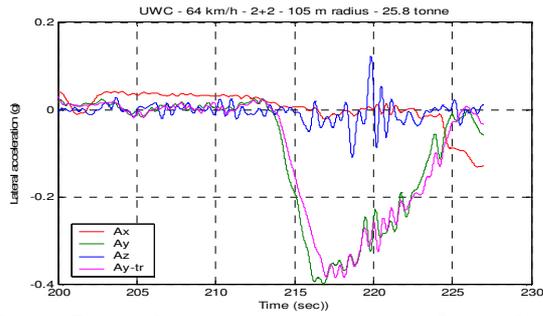
HVTT12: Investigation into the high-speed offtracking characteristics of quad-axle semi-trailers with one or two rear self-steering axles and a review of the high-speed offtracking performance standard

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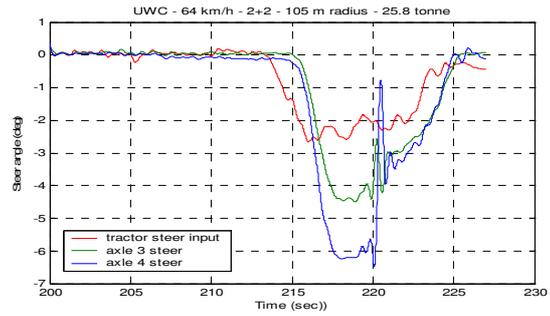**Figure 7: Acceleration versus time – 105 m radius curve – UWC 2+2**

Figure 8: Tractor steer input, trailer axle 3 and 4 steer – 105 m radius curve – UWC 2+2
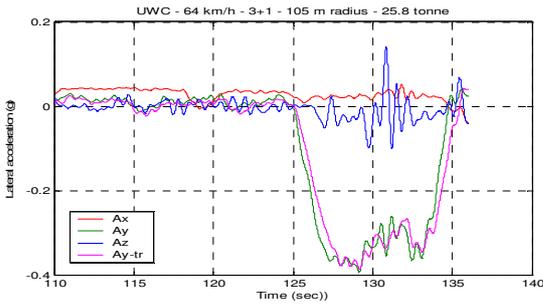

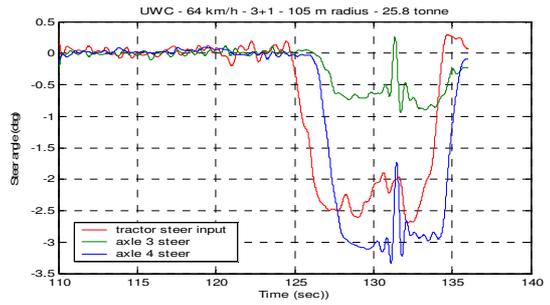**Figure 9: Acceleration versus time– 105 m radius curve – UWC 3+1**

Figure 10: Tractor steer input, trailer axle 3 and 4 steer – UWC 3+1 – 105 m radius curve

Table 1: Peak lateral acceleration and steer angle, tractor axle 1, quad-axle 3 and 4 - 105 m radius

Combination	Peak lateral acceleration (g)	Tractor steer (deg)	Quad-axle 3 steer (deg)	Quad-axle 4 steer (deg)
UWC 2+2	0.40	2.5	4.4	6.2
UWC 3+1	0.39	2.5	0.7	3.1
APC 2+2	0.40	2.5	1.9	3.6
APC 3+1	0.38	2.6	1.5	2.4

5.2   Computer Simulations

Figures 11 to 14 plot offtracking against lateral acceleration for the simulations on the 393 m radius curve for the UWC and APC combinations configured in the 2+2 and 3+1 arrangement. The results for the 2+2 and 3+1 combinations with UWC and APC have been plotted in different groupings to facilitate comparisons to be made. These graphs also plot data for a tri-axle semi-trailer combination to provide a comparison. Included in these graphs are lines indicating reference values at 0.35 and 0.42 m at 0.2 g derived using the RTAC methodology. Also included are lines indicating proposed reference values of 0.6 m at 0.25 g, and 0.8 m at 0.3g.
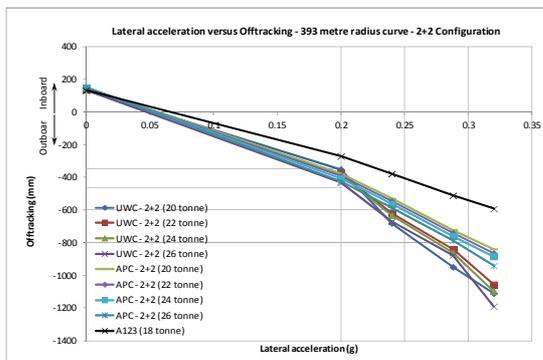

Figure 11: Lateral acceleration versus offtracking – 2+2 quad configuration, UWC and APC

Figure 12: Lateral acceleration versus offtracking – 2+2 and 3+1 quad configuration- UWC

HVTT12: Investigation into the high-speed offtracking characteristics of quad-axle semi-trailers with one or two rear self-steering axles and a review of the high-speed offtracking performance standard
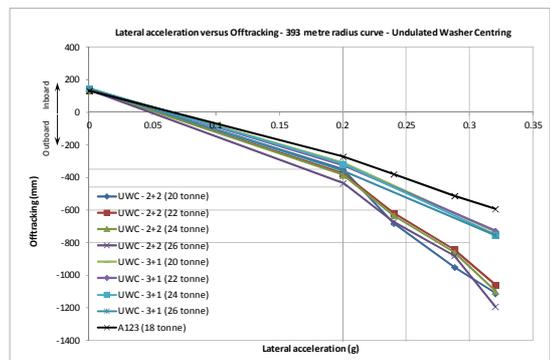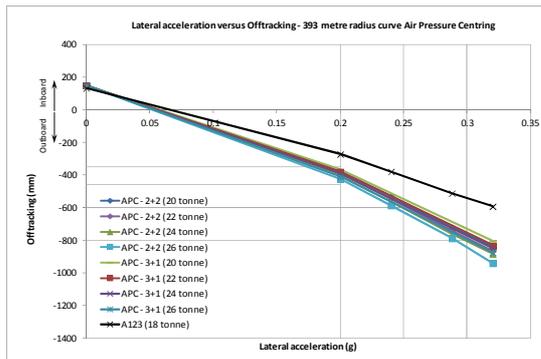
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Figure 13: Lateral acceleration versus offtracking – 2+2 and 3+1 quad configuration- APC
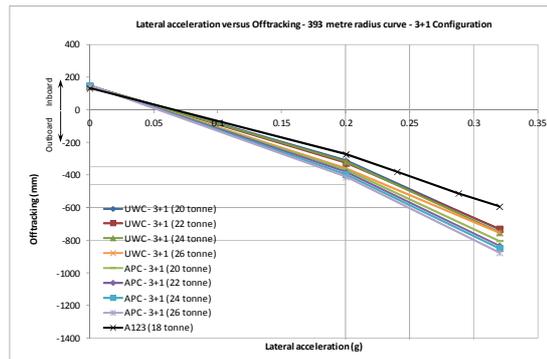

Figure 14: Lateral acceleration versus offtracking – 3+1 quad configuration, UWC and APC

6 Discussion

6.1 High-speed Testing

Analysis of the offtracking measured in the field trials for the UWC quad-axle semi-trailer combination revealed a significant improvement in combination performance when converted to a 3+1 configuration from the baseline 2+2. The 2+2 combination exhibited outboard offtracking even in the 35 m radius curve; at lower speeds the offtracking was inboard, as expected, but transitioned rapidly to outboard offtracking in 40 and 43 km/h tests. This behaviour is highly non-linear and would, therefore, be difficult for a driver to predict. A maximum outboard offtracking amount of 800 mm was recorded for the UWC combination. This was at 43 km/h on the 35 m radius curve with a quad-axle group load of 24.5 tonne. At this speed the combination was close or at its rollover threshold. However, this level of outboard offtracking is highly undesirable in the context of the New Zealand roading environment.

Results of the tests on the 3+1 UWC quad combination, achieved by engaging the reverse lock mechanism of axle 3, show that outboard offtracking was eliminated in the 35 m radius curve tests and reduced from a peak of 700 mm to 150 mm in the 105 m radius test at 62 to 64 km/h. For the 35 m radius curve outboard offtracking of 580 mm became inboard offtracking of 695 mm when converted to a 3+1 combination, a change of 1275 mm. Importantly, analysis of Figure 4 and Figure 5, the offtracking versus lateral acceleration plots, reveals that the behaviour of the 3+1 combination was linear. The linear behaviour agrees with previously published results for tractor semi-trailers and doubles combinations (see Figure 3) – these units did not include a self-steer axle. The performance of a 3+1 combination that utilised a rigid axle, rather than a locked self-steer axle, would be even better, as the free play in the locking mechanism allowed up to one degree of steer in the UWC axle. Without this free play, it is estimated that the maximum steer angle of axle 4 in the 35 m radius turn, at 40 km/h, would be reduced from 6.4 degrees to between 5.0 to 5.6 degrees. Further utilisation of the rigid axle with spring centres wider than the self-steer axles would also improve the roll stability and further reduce the tendency to outboard offtrack by reducing roll steer.

The APC combination in the 2+2 and 3+1 configuration did not produce any outboard offtracking in the 35 m radius curve tests. In the lower speed tests - creep, 30 km/h and 35 km/h - the level of inboard offtacking was similar to the UWC combination. In the 40 km/h test the APC combination still exhibited near linear behaviour. This test was close to the rollover threshold of the combination and a higher speed test could not be conducted as the rollover threshold would have been exceeded. The rollover threshold of the APC combination was lower than the UWC combination primarily due to the reduced spring track of the dual tyre configuration versus the super single configuration of the UWC combination and also a less roll stiff suspension being employed.

In the 105 m radius curve tests, the 2+2 APC configuration had less than half of the outboard offtracking of the UWC combination. Time constraints meant that only the two highest speed tests were run for the 2+2 combination. Creep speed tests were not conducted on the 105 m radius curve, however if creep speed results obtained from computer simulations are substituted in the field test data

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then Figure 5 can be replotted to give an indication of the linearity of the 105 m curve results (this plot is shown in Figure 15). Under this analysis, the 3+1 APC and 3+1 UWC combinations can be considered linear; the 2+2 UWC combination again exhibits highly non-linear behaviour.

The superior performance of the APC combination is solely due to the significantly higher levels of centring force being developed, with the UWC axle having approximately 25 to 30 % of the centring force of the APC axle. This is further evidenced by the maximum steer angle of axle 4 of the 2+2 APC configuration being approximately the same as the maximum steer angle of axle 4 of the 3+1 UWC combination in comparable tests. Actual test data detailing the centring force of both the APC and UWC axles used in these trials is not currently available.
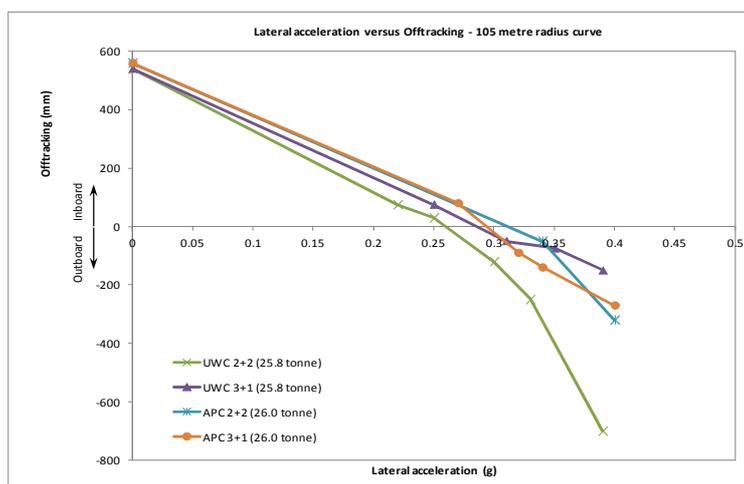
Figure 15: Offtracking versus lateral acceleration – 105 m radius curve – with creep speed results added

Offtracking results for the 3+1 APC configuration did not show significant difference to the 2+2 APC results. Analysis of the steer angle data for the self-steering axles shows that the locking mechanism on the APC allowed over 1.5 degrees of steer, which only reduced the maximum steer on axle 3 by a maximum of 0.4 degrees, (see Table 1).

The torpress pressure for the APC configuration was recorded during the high-speed tests, and in all but one of the tests the pressure in the torpress was between 460 kPa and 520 kPa at entry to the curve. The supplier of the axle recommends the pressure in the torpress be set to 520 kPa for a 22 tonne axle load. The setting of the load sensing valve used to regulate air pressure to the torpress of the test trailer was lower than this. Had the torpress pressures been set at the recommended levels then the outboard offtracking would have been further reduced.

6.2   Computer Simulations of Offtracking Performance

Computer simulations of the UWC and APC combinations used in the field trail were carried out using the Yaw/roll simulation model. Suspension, tyre and self-steer axle data were not available for the combinations tested. The suspension and tyre data used were considered representative, centring force data for the APC axle was based on test data for a Ceschi brand APC axle. This type of APC axle has not been sold in New Zealand for more than 20 years. Further, this centring force data is at least 33 % lower than the centring force data measured by Billing and Patten (2004) at a lower torpress pressure. The centring force data measured by Billing and Patten was for an APC that at least appeared similar to the APC axle used in the field test combination. The centring force data for the UWC axle had previously been reported to cause numerical instability with the self-steer axle subroutine of the Yaw/roll model. To overcome this, the off centre stiffness was increased, this had the effect of making the data more like APC data at low pressures, this would reduce the predicted level of outboard offtracking over the original data. For these reasons, the computer simulations can only be considered to give an approximate representation of the field tested combinations. Nevertheless, they serve to confirm the trends seen in the field test results and provide a comparison between the at speed offtracking performance of quad combinations with low- and high-centring force properties.

The offtracking results for the simulations on the 35 m radius turn indicated increasing non-linearity above 0.2 g lateral acceleration, which was more marked for the 2+2 UWC configurations. Simulations at higher lateral accelerations, although below the rollover threshold of the combination, were not possible as the driver steer subroutine in the Yaw/roll model induced large steer angles at turn entry and these were large enough for the combination to rollover. No outboard offtracking was recorded in these simulations.

Simulations on the 105 m radius turn indicated that the 2+2 UWC configurations transitioned to outboard offtracking between 0.13 and 0.15 g and, overall, had higher levels of outboard offtracking than the 3+1 UWC and 2+2 and 3+1 APC combinations.

Simulations were conducted on a 393 m radius curve at lateral accelerations ranging from 0.2 to 0.32 g. Simulations on lateral accelerations up to 0.35 g were planned but were not possible because of the oscillatory driver model steer input at higher lateral accelerations. The results from these simulations show the 2+2 UWC combination to be highly non-linear above 0.2 g; the 3+1 UWC and 2+2 and 3+1 APC showed less non-linearity. In all cases, the outboard offtracking was greater than a reference tri-axle semi-trailer combination with 18 tonne axle group load. This serves to highlight the effect that even one rear self-steering axle has on HSO performance.

Before the results from the 393 m radius curve can be analysed any further, consideration needs to be given to the HSO reference values. Historically this performance measure has been assessed at 0.2 g with a reference value of 0.46 m – this was proposed as being suitable for the Canadian roading environment. Subsequent analysis by Billing and Patten (2008) has shown that this yields a conservative result in Canada as road design speeds are above 110 km/h and hence the likelihood of exceeding 0.2 g in on-highway cornering is low. Further, generous shoulder widths are provided on the Canadian highway system. Reference values used in New Zealand need to reflect the risk of an outboard offtracking initiated crash in the New Zealand roading environment and should serve to protect the driver from an excessively non-linear vehicle response. The incidence of cornering events above 0.2 g in New Zealand warrants an HSO reference value assessed above 0.2 g. Two such points are proposed and used to further assess the 393 m HSO simulation results. The reference values have been set to ensure that combinations with highly non-linear responses are failed. These additional reference values are 0.6 m at 0.25 g and 0.8 m at 0.3 g. These lateral acceleration levels have been chosen because they are above 0.2 g and below the minimum required SRT level of 0.35 g[2]. Lines indicating these reference values have been included in Figures 11 to 14, as well as lines indicating 0.35 m and 0.42 m reference values at 0.2 g. The rational for these reference values was discussed in Section 3.

Using these reference values excludes all but two of the 2+2 combinations, namely the 2+2 APC combination at 20 and 22 tonne (see Figures 11 to 14); and a clear distinction can be seen between the 2+2 and 3+1 UWC combinations at axle group loads of 20 to 26 tonnes.

7   Conclusions

Field testing of 2+2 quad-axle semi-trailers with low and moderate levels of centring force has shown that they exhibit highly non-linear, outboard offtracking behaviour at lateral accelerations above 0.2 g. This type of vehicle response cannot be predicted by a driver and is highly undesirable.

Field testing of 3+1 quad-axle semi-trailers revealed near linear offtracking response right up to the point of rollover with quad-axle group loads up to 26 tonne.

Computer simulations of the offtracking performance of the field tested combinations confirmed the non linear trends seen in the HSO data recorded during the field trial.

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[2] Since 2002 heavy vehicles in New Zealand have been required to have a minimum SRT of 0.35 g

The current HSO performance measure, adopted from a 1986 Canadian study, has no formal reference value in New Zealand. There has previously been confusion over the test specification and reference value, with a test speed yielding a lateral acceleration of 0.16 g, and a reference value of 0.8 m being used. This is in not in keeping with the original intent of the developers of the high-speed offtracking measure.

A reference HSO value of 0.35 to 0.42 m would be appropriate for use in New Zealand based on the methodology used in the RTAC study and taking into account the New Zealand roading environment.

An additional reference value at a higher lateral acceleration should be included in the HSO performance assessment used in New Zealand; this could be 0.6 m at 0.25 g and/or 0.8 m at 0.3 g. This would ensure that vehicle combinations with highly non-linear responses were detected. All current configuration 2+2 quad-axle semi-trailers, except APC trailers with an axle group load not exceeding 22 tonne, would fail under these proposed measures.

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