

## ROLLOVER CRASH ANALYSIS OF A ROAD TANKER WITH SELF-STEER AXLES



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### Abstract

In March of 2006 a rollover crash occurred in New Zealand involving a cryogenic road tanker comprising a twinsteer prime mover towing a quad-axle semi-trailer with two self-steer axles in the rearmost positions of the quad-axle set. The crash occurred on a long sweeping bend and involved a clean separation between the prime mover and the semi-trailer at the turntable connection. There were no injuries in the incident only damage to the tanker semi-trailer and local property. To determine the cause of the rollover a detailed survey of the crash site was made accompanied by an extensive investigation using state-of-art numerical modelling of vehicle dynamics. The numerical modelling showed the baseline vehicle to have poor high-speed off-tracking performance, which was found to be very sensitive to speed. These two factors, in combination with overloading (if it occurred) and speed management, appeared to be the main contributing factors that led to the rollover crash. A review of self-steer axle policy has been carried out by the regulating authorities in New Zealand.

**Keywords:** Heavy vehicle, rollover, road tanker, self-steer axles, quad axles, performance-based standards, numerical modelling, dynamics, stability, high-speed offtracking.

### Résumé

En mars 2006, un poids lourd transportant des fluides réfrigérant s'est renversé en Nouvelle Zélande. Ce poids lourd était composé d'un tracteur à double essieux directeurs et d'une remorque à quatre essieux, dont deux indépendants, positionnés à l'arrière de cette remorque. L'accident s'est produit dans un grand virage et a conduit à la séparation du tracteur de la remorque. Il n'y a pas eu de blessés, mais juste des dégâts matériels. Pour déterminer la cause du renversement, une étude détaillée des lieux de l'accident a été faite, ainsi qu'une revue de l'état de l'art sur la modélisation numérique de la dynamique du véhicule. La modélisation numérique a montré que le véhicule de base avait de faibles performances en termes de balayage à vitesse élevée, ces performances étant très sensibles à la vitesse. Ces deux facteurs, combinés à la surcharge (si elle a eu lieu) et la gestion de la vitesse, semblent être les principaux facteurs qui ont conduit au renversement. Une revue de la réglementation des essieux autoporteurs a été effectuée par les autorités de Nouvelle-Zélande.

**Mots-clés:** poids lourd, renversement, transport de liquide, essieux autoporteurs, essieux quadri, normes performanciennes, modélisation numérique, dynamique, stabilité, balayage à vitesse élevée.

## 1. Introduction

In March of 2006 a rollover crash occurred in New Zealand involving a road tanker comprising a twinsteer prime mover towing a quad-axle semi-trailer. The crash occurred on a long sweeping bend and involved a clean separation between the prime mover and the semi-trailer at the turntable connection, with subsequent rollover of the quad-axle semi-trailer unit in a nearby rural pasture where it came to rest. There were no injuries in the incident only damage to the tanker semi-trailer and local property damage. An example CO<sub>2</sub> road tanker, identical to the one involved in the rollover incident, is shown in Figure 1.



**Figure 1** – Example CO<sub>2</sub> road tanker  
(semi-trailer self-steer axles are in positions 3-4, the two rearmost axles).

Investigation of the rollover involved a combination of crash site inspection and survey, and state-of-the-art numerical modelling of vehicle dynamics. A range of vehicle performance measures was considered consistent with the latest set of Performance-Based Standards (PBS) developed jointly by National Transport Commission (NTC) and Austroads in Australia (National Transport Commission, 2005). Using three whole-of-vehicle numerical models, vehicle performance was considered both in relation to the standard set of PBS manoeuvres and in a separate manoeuvre closely representing the conditions that led to the rollover.

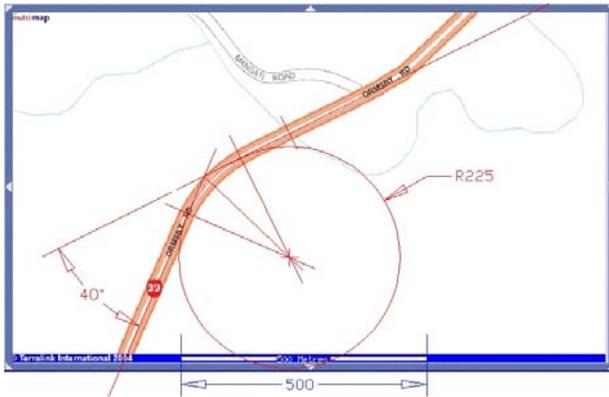
## 2. Rollover Incident

### 2.1 Location

The rollover occurred on Ormsby Rd of State Highway 39 near to Mangati Rd bridge south of Pirongia township in New Zealand. A locality map is presented in the left image of **Figure 2**, which identifies the bend on which the rollover occurred. The vehicle was travelling northbound, in a NNE direction. This road, previously a Provincial Highway (“country road”), had recently been designated a State Highway. (The highways in New Zealand were originally designated on a two-tier system, National and Provincial, with national highways having a higher standard and funding priorities. Now all are State Highway.) The right image in **Figure 2** (looking southbound) was taken on the bend and shows this section of road to have a traffic lane width (distance from centre line to edge-line) of about 3 m, a shoulder width of about 0.5 m (edge-line to edge-of-seal) with a gradual then rapid drop off, respectively, at the verge and batter.

### 2.2 Horizontal Alignment

Road data collected as part of a routine high-speed road survey were made available to the investigation by Land Transport NZ (LTNZ). The data included gradient, horizontal curvature and crossfall, both on the bend and along 500 m sections on each of the straight approaches to the bend. The left image of **Figure 2** shows that, in broad terms, the horizontal alignment comprises a change of heading through an angle of about 40° along a 225 m radius circular arc, consistent with the road data supplied by LTNZ.



**Figure 2** – Location of bend on which the rollover occurred (left image, from <http://www.multimap.com>), and traffic lane and edge detail (typical).

Photographs taken by BOC Ltd at the site of the rollover are reproduced below in **Figure 3**. These show the following points of note: northbound approach to the bend and the 75 km/h advisory speed sign (top-left image); a view in the southbound direction partway through the bend (top-right image); a dip in the road surface at the start of bend (lower-left image); and, the straight approach on the exit side of the bend together with the final resting position of the rolled tanker semi-trailer and adjoining property damage (lower right image).



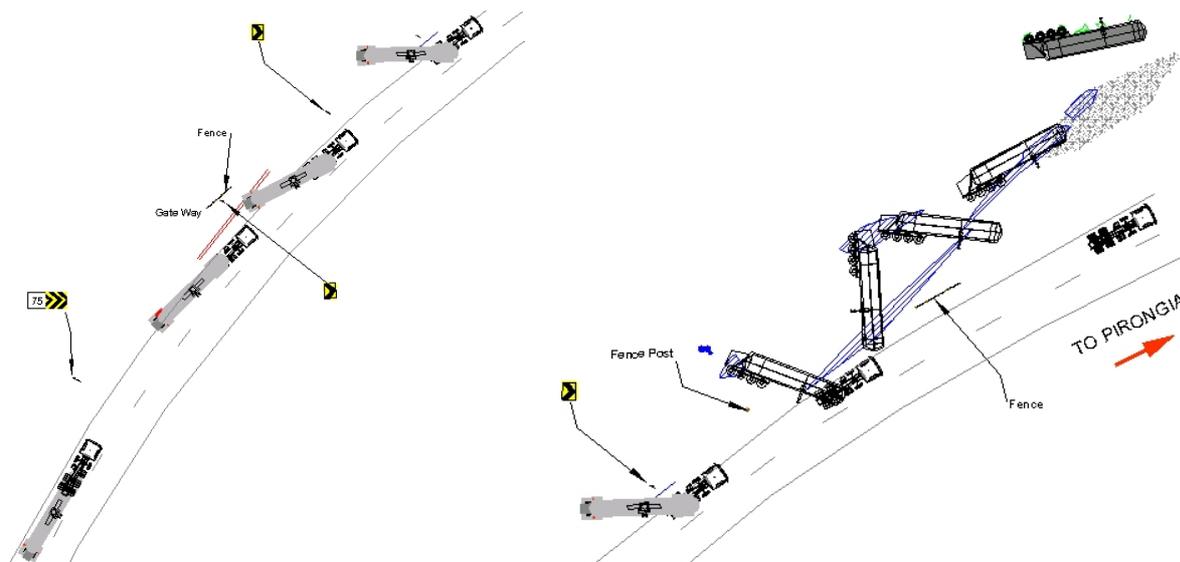
**Figure 3** – Photographs taken by BOC Ltd at the site of the rollover

### 2.3 Rollover and Follow-up Investigations

Soon after the rollover incident occurred Crash Scene Investigation Ltd (CSI), New Zealand, carried out a detailed survey of the crash site. The survey recorded the location and length of tyre marks, gouge marks and debris throw. From this survey CSI constructed a scene map

and developed a scenario of likely events that commenced just before the first tyre marks appeared and concluded when the tanker semi-trailer came to rest. The scene map and rollover scenario is reproduced below in **Figure 4**. The following description prepared by the authors of this paper accompanies the rollover scene pictorials presented below:

- a) Upon entering the bend the tanker semi-trailer experiences excessive and increasing levels of high-speed offtracking;
- b) As the high-speed offtracking continues to increase the tyres on the quad-axle group, which are now operating at a large slip angle that continues to increase, move out of the traffic lane (sealed pavement) onto the verge and batter which falls away rapidly (initial part of right-side image in **Figure 4**);
- c) The tyres on the quad-axle group now sliding sideways along the batter on uneven soft terrain catch and trip the tanker semi-trailer. The large articulation angle that has developed, and the resulting large forces and moments acting on the turntable as the semi-trailer rapidly slows, causes the turntable to fail, tearing it from its mounts commencing at the rear right corner;
- d) A clean separation occurs between the semi-trailer and the prime mover;
- e) The tanker semi-trailer continues to tumble and roll until it comes to rest while the prime mover now free of the semi-trailer continues unimpeded along its path.



**Figure 4** – Initial and final stages of the rollover sequence, left and right images respectively, as recorded by the crash survey.

### 3. Vehicle and Numerical Models

#### 3.1 Road Tanker

The BOC road tanker comprises a twinsteer tandem drive prime mover towing a purpose built quad-axle tanker semi-trailer at an overall length of 17.825 m. Under current mass limits in New Zealand the road tanker can operate at a gross combination mass (GCM) of up to 45.5 t (comprising of 44.0 t plus a 1.5 t tolerance), made up of the following maximum axle loads: 10.8 t on the twinsteer, 15.0 t on the tandem drive and 20.0 t on the quad-axle group. The cryogenic tanker semi-trailer has a maximum payload capacity of about 28 t, carrying liquid CO<sub>2</sub> (carbon dioxide) at minus 22°C in an insulated stainless steel vessel.

### ***a) Prime Mover***

The prime mover is powered by a 550 hp engine. It has a taper-leaf spring non-load-sharing twinsteer front suspension. The drive group features an airbag suspension. The steer axles and the drive axles both run on 275/70R22.5 low profile tyres operating at an inflation pressure of 620 kPa/6.2 bar (90 psi).

### ***b) Tanker Semi-trailer***

The purpose-built cryogenic quad-axle tanker semi-trailer is built in Australia and is fitted with axles manufactured in Europe. Consistent with the heavy vehicle regulations in New Zealand, the two lead axles on the quad axle set, front-front (positions 1-2), are both rigid axles (non-steering), and the two rear axles, rear-rear (positions 3-4), are both self-steer axles. The self-steer axles have a maximum of 16° steer lock, satisfying the 15° minimum steer lock New Zealand requirement. All four axles feature trailing arm airbag suspensions running on 385/65R22.5 wide single tyres and operating at an inflation pressure of 620 kPa/6.2 bar (90 psi).

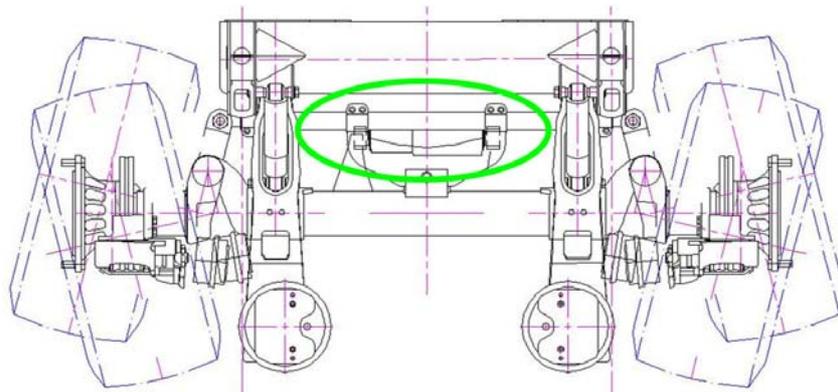
### ***c) Self-Steer Axles***

The performance of the self-steer axles fitted to the quad-axle set of the tanker semi-trailer is central to this investigation. Three separate arrangements were considered in the analysis.

The first arrangement, referred to as the baseline, is the system that was installed on the road tanker involved in the rollover incident. The second system considered in the analysis is a later model of the first system. This has been in manufacture from 2005 and features a different self-centralising mechanism. The third system considered simply removes the steer action from the self-steer axles.

### **Baseline Self-Steer Axle**

A plan view drawing of the baseline self-steer axle arrangement is shown in **Figure 5**. The basic self-tracking or self-steer function derives from castor action of the wheels resulting from the forward-set steer axis. As shown, to achieve the desired steer geometry the left and right-side wheels are connected by a tie-rod through forward projecting steering arms connected to each stub axle.



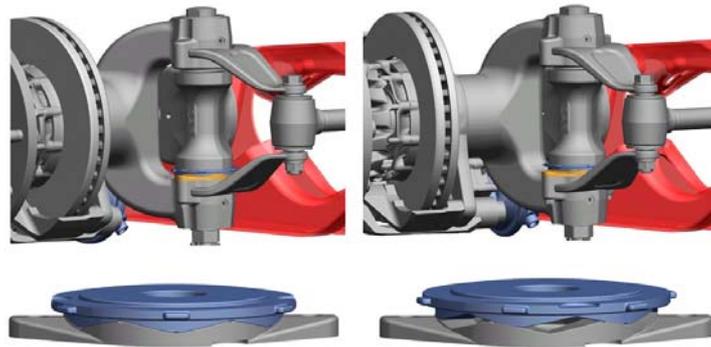
**Figure 5** – Baseline self-steer axle showing range of steer movements and centrally located spring arrangement (shown circled) for self-centring.

For the baseline version of the self-steer axle the centralising moment is produced by a pre-tensioned bi-directional spring contained in a “shock absorber” type housing. At one end the spring in its housing is attached to the tie rod and at the other end to the axle. This arrangement produces a centralising moment that is independent of axle and wheel load.

### Later Model Self-Steer Axle

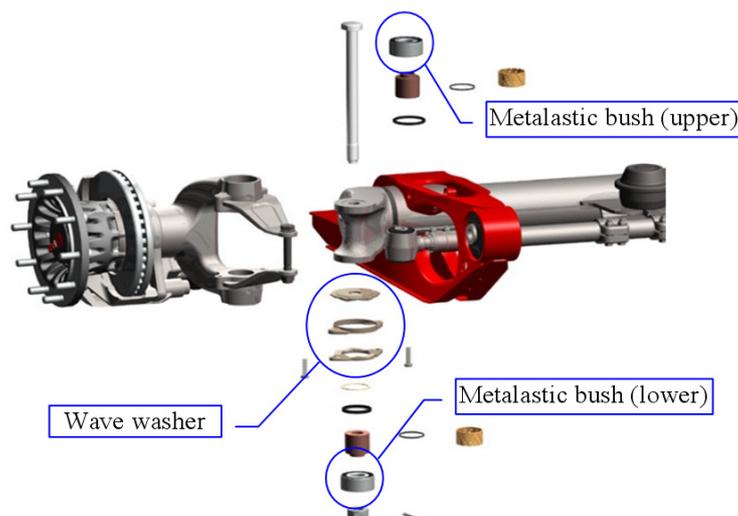
In the later model version of the self-steer axle, the mechanism for providing the centralising moment has been changed. Details of the mechanism for providing the centralising moment are disclosed in **Figure 6** and **Figure 7**.

The two key elements of the later model self-steer axle, the “wave washer” and “metalastic” bush, are shown in the exploded view of the steering knuckle as **Figure 7**. The wave washer produces a centralising moment that is: 1) dependent on the steepness of the angle of the inclined mating surfaces and the friction between them; and, 2) proportional to the vertical force on the steering axis (the wheel load). The centralising moment from the second mechanism is independent of steer angle.



**Figure 6** – Later model self-steer axle shown in the straight-ahead (top-left) and off-centre steered positions (top-right) together with corresponding alignment of the “wave washer”.

In addition, the metalastic bush provides a clamping force across the wave washer inducing an additional centralising moment proportional to the applied preload and the product of the axial stiffness of the metalastic bush times the steer angle. A high preload and stiff metalastic bush produces a proportionally higher centralising moment that increases more rapidly with steer angle. If the clamping force is large enough, and the stiffness of the metalastic bush high, the joint could theoretically become locked and there would be no self-steer freedom.



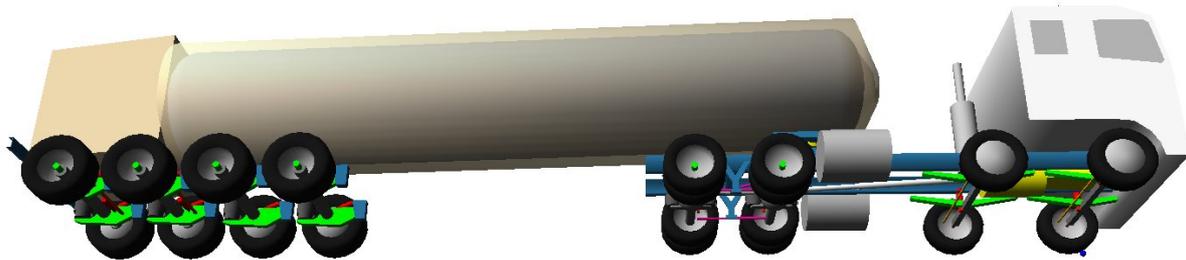
**Figure 7** – Exploded view of the later model self-steer axle steering joint

The centralising steer properties of the later model self-steer axle were determined by the manufacturer through a series of physical measurements. These data were made available to the authors.

### 3.2 Numerical Models

For the analysis three numerical models were created using the ADAMS multi-body dynamics simulation software package (MSC.Software, 2007) and MSD's *Atruck*<sup>TM</sup> toolbox. The three models were identical except for the two self-steer axles on the quad-axle set, which were designed to represent, respectively, the baseline self-steer axle ("Baseline"), the later model self-steer axle ("Later Model"), and self-steer axles without steer freedom ("Rigid Axles"). The mechanical properties of each of the modelled self-steer axles were consistent with the descriptions and information supplied by the manufacturer.

A general view of the numerical model, as well as specific details related to the prime mover and tanker semi-trailer, are shown below in **Figure 8**.



**Figure 8** – General view of the numerical model of the BOC road tanker.

Mechanical properties were assigned to components (sprung and unsprung masses, suspension, tyres, etc) in each of the models consistent with the components installed on the road tanker involved in the rollover incident. Typically, data were obtained from manufacturers and component suppliers. Where vehicle, system or component level information could not be obtained, representative data from a previous major study of the performance of the Australian heavy vehicle fleet (Prem et al, 2002) were used. Where necessary, information was sourced from MSD's extensive heavy vehicle database and library.

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 (self-steer axles, tyres, airbags, shock absorbers, for example) the component models were adjusted and tuned to accurately reproduce the measured properties.

## 4. Simulations

### 4.1 Performance Based Standards (PBS)

Drawing on the latest set of Performance-Based Standards (PBS) (National Transport Commission, 2005) a range of vehicle stability and dynamics performance issues was considered. Vehicle performance was investigated both in relation to a selection of performance measures from the standard set of PBS manoeuvres, which are also closely linked and aligned with the standards that have been used in New Zealand for assessing vehicle stability and dynamics, and in a separate manoeuvre closely representing the conditions that led to the rollover incident.

Four GCM load conditions were considered as defined below in Table 1. These cover both acceptable load conditions and a range of higher load scenarios up to a maximum of 50.5 t.

The following PBS performance standards were considered in the investigation of high-speed stability and dynamics: *Tracking Ability on a Straight Path*; *Static Rollover Threshold*; *Rearward Amplification*; *High-Speed Transient Offtracking*; and *Yaw Damping Coefficient*.

**Table 1** – GCMs and axle group load combinations considered in the analysis.

Gross Combination Mass (t)	Steer (t)	Drive (t)	Semi-trailer (t)
45.8	10.8	15.0	20.0
48.8	10.8	16.0	22.0
50.0	10.8	16.7	22.5
50.5	11.0	15.5	24.0

These are a subset of the complete set of approved PBS standards and relate specifically to safety performance directly relevant to this assessment. Complete formal descriptions and detailed definitions can be found in National Transport Commission (2005).

**4.2 Rollover Incident**

For the simulations of the actual rollover conditions a perfectly flat surface was assumed and a simplified horizontal curvature profile was used. This approach was considered more conservative than using a fully developed three-dimensional surface profile based on the measured road data. While this assumption may hold in broad terms, specific detail, such as the dip on the approach to the curve, identified in **Figure 3** (lower-left image), has been ignored in this analysis. This road feature may be significant – as it would tend to destabilise the vehicle at the point of entry into the bend – and could be considered an additional contributing factor that may require follow-up in any future investigations.

Simulations were conducted for a range of constant travel speeds, commencing at 75 km/h (the posted advisory speed for this particular bend) and increased in increments of 5 km/h up to a maximum speed of 95 km/h, the maximum speed permitted by law, comprising the 90 km/h speed limit for heavy vehicles to which has been added the 5 km/h speed enforcement tolerance (Land Transport NZ, 2006b). Additional simulations were also performed at speeds greater than 95 km/h up to the point where rollover occurs.

For analysis of the rollover incident, high-speed offtracking of the outside wheel of the trailing axle was calculated and the maximum value recorded as the performance value in this manoeuvre. The measure records the lateral distance that the outermost quad-axle tyre tracks outside the path of the front steer tyre of the prime mover.

**5. Results and Discussion**

**5.1 Performance Based Standards**

While five PBS performance standards were considered in the full analysis, only the following two, static rollover threshold and high-speed transient offtracking, were found to be significant with respect to the key findings. As a result, the focus of the discussion is restricted to these two performance standards.

**a) Static Rollover Threshold**

The performance values from the PBS 100 m radius steady-turn manoeuvre for each of the three variants at each GCM considered is presented in convenient summary form below in Table 2, which also compares, in percentage terms, the performance change of each variant relative to the 45.8 t Baseline vehicle. These show that the Baseline, Later Model and Rigid

Axles variants of the road tanker are all able to meet the 0.40g PBS Level 1 (L1) performance requirement only at the 45.8 t GCM, with the Baseline having the lowest value (0.41g) and the Rigid Axles variant having the highest value (0.43g). Only the Rigid Axles variant is able to satisfy the PBS performance requirement at the higher GCMs. The Baseline and Later Model variants are not able to meet the 0.40g PBS performance requirement at any of the higher GCMs.

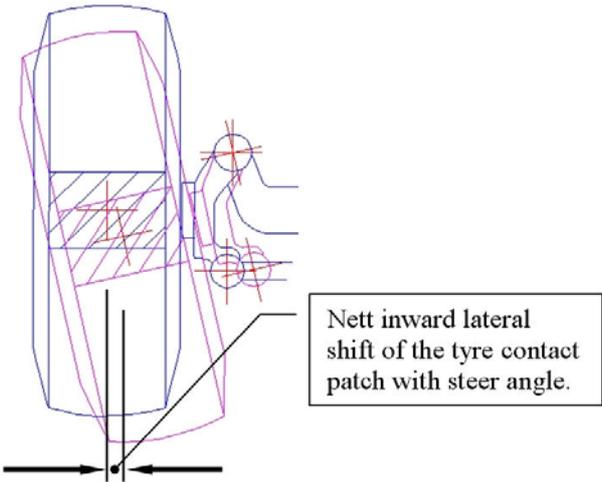
Table 2 shows static rollover stability improving as the centralising moment on the self-steer axle increases, from the Baseline to Later Model variants (0.2%), and to the Rigid Axles variant (3.4%).

**Table 2** – PBS results for static rollover threshold.

GCM (t)	Performance Value (g)			Change relative to 45.8 t Baseline Vehicle		
	Baseline	Later Model	Rigid Axles	Baseline	Later Model	Rigid Axles
45.8	0.417	0.418	0.431	0.0%	0.2%	3.4%
48.8	0.398	0.398	0.412	-4.6%	-4.6%	-1.2%
50.0	0.390	0.389	0.403	-6.5%	-6.7%	-3.4%
50.5	0.398	0.396	0.411	-4.6%	-5.0%	-1.4%

The sensitivity of static rollover threshold to the steer centralising moment and/or maximum steer angle of the self-steer axle can be easily explained by reference to **Figure 9**, which illustrates how the self-steer action leads to a reduction in the effective wheel track width.

Finally, Table 2 shows that the rollover stability of the 50.5 t road tanker is about 2% higher than the stability of the 50.0 t variant. This is a direct result of the higher load on the quad-axle group, which has higher roll stiffness than the drive axle group and is able to provide greater resistance to overturning.



**Figure 9** - Illustration of inward migration of the tyre contact patch with steer-angle leading to a nett reduction in effective vehicle track width

**b) High-Speed Transient Offtracking**

The results from the PBS lane change simulations presented below in Table 3 show the Baseline, Later Model and Rigid Axles variants of the BOC road tanker at each of the GCMs considered would satisfy the PBS performance requirement ( $\leq 0.6$  m) for access to PBS Level 1 (L1) road class routes.

It is useful to note that a similar performance requirement is contained in New Zealand’s “Steerable Rear Axles Policy” (LTSA, 1996). The policy applied to triaxle sets with rear axle self-steering. A 0.6 m performance limit for high-speed transient offtracking was used to establish minimum centring force (restoring moment) requirements on self-steer axles at speeds above 40 km/h. Alternatively, a pin or system that locks the wheels in the straight-ahead position could be used at speeds above 40 km/h. The performance requirement was designed to “ensure sufficient lateral guidance at speed while cornering” (LTSA, 1996). The policy has since been superseded by the latest rules, which simply requires self-steer axles to be capable of steering through an angle of at least 15°, which is useful in low-speed turns only. For high-speed operation the rule requires the distribution of the gross mass of a motor vehicle over its axles, and position of the centre of gravity of the vehicle, must ensure that the dynamic handling characteristics of the vehicle remain safe in terms of stability and steering manoeuvres for the design-speed of the road. The vehicle must be manoeuvrable, fit safely on the road and interact safely with road users.

The summary presented in Table 3 shows that substantial improvements (reductions) in high-speed transient offtracking occur between the Baseline and Later Model variants, and further significant improvements are apparent between the Later Model and Rigid Axles variants.

**Table 3 – PBS results for high-speed transient offtracking.**

GCM (t)	Performance Value (m)			Change relative to 45.8 t Baseline Vehicle		
	Baseline	Later Model	Rigid Axles	Baseline	Later Model	Rigid Axles
45.8	0.437	0.229	0.173	0.0%	-47.6%	-60.4%
48.8	0.467	0.254	0.184	6.9%	-41.9%	-57.9%
50.0	0.474	0.265	0.189	8.5%	-39.4%	-56.8%
50.5	0.481	0.264	0.188	10.1%	-39.6%	-57.0%

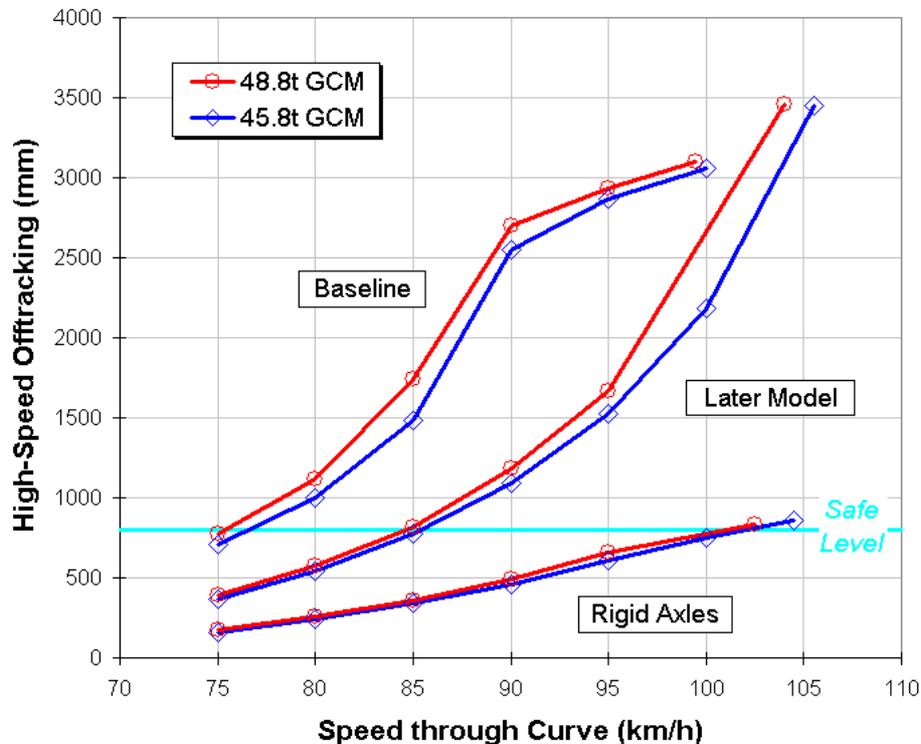
These improvements are a direct result of the additional tyre side-force capability due to the increased resistance to the self-steer action in the Later Model variant, and complete elimination of the self-steer function in the Rigid Axles variant. For the Rigid Axles variant, for example, on the tanker semi-trailer quad-axle group, eight tyres are generating side force at a small tyre slip angle compared with the Baseline, which requires four tyres to generate about the same side force but at a larger slip angle. The relationship between tyre vertical load, tyre side-force and tyre slip angle is highly non-linear leading to a rapid increase in slip angle, and hence a rapid increase in high-speed offtracking with increasing side-force demand.

**5.2 Rollover Incident**

The main results from the simulation of the rollover incident are presented in **Figure 10**, which shows the maximum value of high-speed offtracking for a range of speeds. It is important to note that the maximum value of high-speed offtracking normally occurs early, for example, when the rear end of the vehicle is about three vehicle lengths into the bend, consistent with **Figure 4**.

Also shown in **Figure 10** is an assumed high-speed offtracking “Safe Level”, set at a value of 0.8 m. This value is made up of the 0.6 m from the PBS high-speed transient offtracking Level 1 (L1) performance requirement, which is consistent with the performance requirement specified in the former “Steerable Rear Axles Policy” (LTSA, 1996), to which has been added an allowance of 0.2 m corresponding to about half the width of the wide single tyre. A safe

level of 0.8 m is consistent with the usual acceptability standard for high-speed steady-state offtracking reported in de Pont (2004). This safe level would ensure no tyre drops off the sealed surface thereby reducing the risk of rollover due to adverse cross-slope even if the vehicle has not yet reached its rollover limit due to lateral acceleration.



**Figure 10** - Summary of results from rollover incident simulations

Given the above, it is important to note that the traffic lane and shoulder width details shown in **Figure 2** for this particular road suggests that offtracking of 0.8 m could be safely accommodated only if the road tanker is located either in the centre of the lane, with no margin for error, or, preferably, nearer to the centreline, giving the driver a small margin for error. However, in the presence of oncoming traffic, either scenario would present the driver with a greater workload and increase the likelihood of running wide of the lane centre.

With the above assumptions in place, **Figure 10** shows that if the vehicle is travelling at the posted advisory speed of 75 km/h, each of the three variants at each of the two GCMs (45.8 t and 48.8 t) could safely negotiate the bend. However, an increase in speed of just 5 km/h to 80 km/h would cause the Baseline variant to exceed the assumed high-speed offtracking safe level at either of the two GCMs. **Figure 10** shows clearly that any further increases in speed lead to very rapid increases in high-speed offtracking, made marginally worse by increases in the GCM. LTNZ Heavy Vehicle Road Code states that heavy vehicles should reduce speed to 10 km/h below advisory postings, particularly when laden, consistent with BOC Ltd standard procedures.

For the baseline vehicle the above paints a picture that is consistent with the scenario presented in **Figure 4**, and shows excessive levels of high-speed offtracking near to the entry point to the curve would be likely to occur. This suggests the main factors that led to the rollover were:

- 1) Poor high-speed offtracking performance;
- 2) The sensitivity of high-speed offtracking to speed;

- 3) Overloading (if it occurred);
- 4) Speed management (at the point of entry and through the bend); and
- 5) Despite BOC's operator specifying high levels of vehicle safety equipment, several vehicle faults were identified, including faulty wiring and function in the prime mover's electronic brake controls, faulty ride height control and loose tie rod ends in the steering arms on the two steer axles.

The first two factors and fifth listed above relate specifically to the vehicle. The first two factors, in particular, relate to the design and performance of the self-steer axle. The third factor is operational and the fourth is driver related. Other additional factors may also have contributed to the rollover incident, such as the dip in the road on the approach/entry to the bend, identified in **Figure 3** (lower-left image), steer corrections made by the driver at the point of entry to the bend in response to the bump, and the influence of liquid slosh in the tank. These additional factors were not investigated and are considered not as significant as high-speed offtracking.

As clearly shown in **Figure 10**, the Later Model vehicle variant exhibits a marked improvement in high-speed offtracking performance, exceeding the safe level offtracking only at a speed of about 85 and 86 km/h at the higher and lower of the two GCMs considered, respectively. A further more substantial improvement in high-speed offtracking is exhibited by the Rigid Axles variant, further raising the safe-level speed to just above 100 km/h at either of the two GCMs. Also, the high-speed offtracking for the Rigid Axles variant does not exceed a value greater than about 870 mm even at a speed that causes the vehicle to rollover.

## **6. Concluding Commentary, Policy Issues and Performance Based Standards**

- 1) The findings of this investigation have been confirmed by in the field testing conducted by BOC Ltd. Specifically, the later model self-steer axle system, as described in this report, when fitted to the BOC road tanker is considered acceptable in respect of stability and dynamics, except for steering wobble on undulating roads, which has been addressed through the fitment of steering dampers and a different suspension.
- 2) A formal performance requirement should be established for evaluating self-steer axles that requires specific levels of high-speed offtracking to be demonstrated under both transient (lane change) and steady turn conditions, similar to those used in this investigation. This would need to be designed to ensure that any gaps or perceived gaps in the current regulations are addressed.
- 3) An alternative to Item 2) above would be to impose the requirement that self-steer axles be locked in the straight-ahead position above a specified speed and unlocked at the same or a lower speed. This has the added advantage of ensuring rollover stability is not compromised and minimum levels of high-speed offtracking are maintained. When transitioning through the set threshold speed, and in order to ensure the axles remain locked when conditions are unfavourable or would otherwise compromise the safety of the turning vehicle, the system could be designed to be responsive to turn conditions by additionally sensing – either individually or in combination – the vehicle's lateral acceleration, yaw rate and articulation angle, for example. (The road tanker is now fitted with a steer lock on the self-steer axle in position 3, however, testing is still in progress to determine the most appropriate speed at which the lock is

engaged, and in-service operation will be subject to changes to the regulations in New Zealand.)

- 4) If the locking system described in Item 3) above is implemented in the self-steer system, and subject to confirmation by in-the-field testing, the performance of the BOC road tanker should be considered acceptable at GCMs of up to 50.0 t.
- 5) Other self-steer axle systems and vehicle combinations on which they are used should be investigated for stability and dynamic performance using methods identical or similar to those presented in this report.
- 6) The findings of this investigation are directly relevant to the development of performance-based standards in Australia and should be considered by the National Transport Commission (NTC) and Austroads.

## 7. Acknowledgements

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## 8. References

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