A review of the high-speed offtracking characteristics of quad-axle semitrailers with two self-steering axles, and a review of the high-speed offtracking performance standard

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Objective

To quantify the high-speed offtracking performance of quad-axle semi-trailers with 1 or 2 rear self-steering axles.

- Review of the high speed offtracking performance measure
- Review of previous studies of heavy vehicles fitted with self steer axles
- Review of the cornering speeds of heavy vehicles
Background – mass and dimension regulations

• Transport regulations covering mass and dimensions were converted to a Land Transport Rule in 2002
• No change to the 44 tonne combination mass or 20 metre overall length limits
• Proposal to allow semi trailers to have
  – 4 axles
  – 24 tonne maximum axle group load
  – 18 metre overall length limit
  – 44 tonne combination mass limit
• Proposed quad axle semi required to have
  – Single rear self steering axle
  – 3.6 to 4.0 metre axle group spacing
Background – mass and dimension regulations
Background – mass and dimension regulations

• A 20 tonne group limit was imposed due to bridge long member capacity issues

• Concern was raised by several Road Controlling Authorities that the 4 metre axle group spacing would produce significant horizontal pavement forces

• To alleviate this concern the quad axle group was required to have two self-steering axles, either in positions 1 and 4 or 3 and 4

• Axle set spacing requirements and the defined location of the rear axis meant that the majority of semi trailers with quad axle sets have self steering axles in positions 3 and 4 (2+2 configuration)

• Detailed requirements for the setup and specification of self-steering axles were not carried over into the Land Transport Rule
2+2 quad-axle semi-trailer

- Large first to last axle spacing enables higher mass - 44 tonne
- Rear steer axles minimise low speed offtracking
New Zealand roading environment

- NZ roads are hilly and winding
  - 48% of roads are on flat terrain
  - 30% are on rolling terrain and
  - 22% are on mountainous terrain

- There is approximately one horizontal curve of 750m or less in radius for every 2 km of State Highway. Half of these are 250m or less in radius
New Zealand roading environment

- Sealed shoulders are narrow and in places non-existent
- The margin for error is very small
New Zealand roading environment
Issues

- Quad axle semi trailer with two rear steering axles (2+2) were not field tested before their introduction in 2002
- 2+2 quad configuration unique – not used anywhere else in the world
- Tracking performance of the 2+2 quad both at low and high speeds had been implicated in crashes
Method – Field Testing

- Two quad axle semi trailers used for high speed testing
  - Undulated washer centring
  - Air pressure centring
- Each trailer could be converted between the 2+2 and 3+1 configuration
- Two 90 degree curves
  - 35 metre radius
  - 105 metre radius
- Quad axle loads of 22, 24 and 26 tonne
- Lateral accelerations of 0.1 g up to the rollover limit

(Test track did not allow testing to the RTAC high speed offtracking performance measure)
Method – Field Testing

- Each combination fitted with data acquisition equipment and a spray system to allow offtracking to be measured
- Outriggers fitted to prevent rollover
Self steer axles

- Self steer axles on the test trailers were leading kingpin automotive steer type
- Centring force varied from moderate for the undulated washer type to high for the air pressure centring axle
- Centring force for both axle variants is load dependant
Self steer axles

Centering moment versus steer angle

- Ceshci @ 80
- Ceshci @ 60
- Ceshci @ 40
- UWC @ 5.5 tonne axle load
- UWC - revised @ 5.5 axle load
Self steer axles

Billing, J.R. and J.D. Patten, Full Scale Performance Testing of 5-axle Semitrailers, 2004,
Results – Field tests
Results – Field tests

- Steer angle on axles 3 and 4
- UWC
- 105 m radius
- 64 km/h
- 26 tonne
Results – Field tests - 35 metre radius

Offtracking versus Lateral acceleration - 35 metre radius curve

Outboard Inboard

Lateral acceleration (g)

Moderate 2+2 (24.5 t)
Moderate 3+1 (24.5 t)
Moderate 2+2 (25.8 t)
Moderate 3+1 (25.8 t)
High 2+2 (26 t)
High 3+1 (26 t)
Results - Field tests – 105 metre radius

![Graph showing offtracking versus lateral acceleration for different vehicle configurations.](image)

- Offtracking versus Lateral acceleration - 105 metre radius curve
- Outboard Inboard

- Moderate 2+2 (25.8 tonne)
- Moderate 3+1 (25.8 tonne)
- High 2+2 (26.0 tonne)
- High 3+1 (26.0 tonne)
Observations

- High speed offtracking response of 2+2 quads with moderate centring force is highly non-linear
- Noticeable difference in performance between 2+2 and 3+1 configurations – driver commented that the 3+1 combination was ‘calmer’
- Centring force has large impact on high speed offtracking
Offtracking versus Lateral acceleration

Computer simulations – Results – 393 metre radius

Offtracking versus Lateral acceleration - 393 metre radius curve - Moderate Centring Force

- Outboard
- Inboard

- Moderate - 2+2 (20 tonne)
- Moderate - 2+2 (22 tonne)
- Moderate - 2+2 (24 tonne)
- Moderate - 2+2 (26 tonne)
- Moderate - 3+1 (20 tonne)
- Moderate - 3+1 (22 tonne)
- Moderate - 3+1 (24 tonne)
- Moderate - 3+1 (26 tonne)
- A123 (18 tonne)
Centring force level – effect on HSO

Offtracking versus Lateral acceleration

- Offtracking (mm)
- Lateral acceleration (g)

Key:
- A123 (18 tonne)
- SDC - BOC crash report
- KPC - BOC crash report
- Rigid axle report
- KPC - 2+2 (22 tonne)

Legend:
- Low
- Moderate
Cornering Speeds of Heavy Vehicles

- Speed surveys of laden heavy vehicles on posted advisory speed curves showed that:
  - Laden heavy combination vehicles travelled through on average 11% faster than the posted advisory speed
  - This reduced to 6% above the posted advisory speed for high centre of gravity vehicles

- Analysis of lateral acceleration data recorded from a line haul B-train combination showed that:
  - On average three to four cornering events above 0.22 g were recorded on a return trip from Auckland to Wellington (≈ 1300 km)

- Analysis of speed and position data from electronic hubodometers showed that:
  - The average cornering speed is at or above the posted advisory speed
  - Average speeds giving rise to lateral accelerations above 0.2 g were recorded on all curves of 200 metres radii and less
## Cornering Speeds of Heavy Vehicles

<table>
<thead>
<tr>
<th>Radius (m)</th>
<th>40</th>
<th>100</th>
<th>150</th>
<th>200</th>
<th>250</th>
<th>300</th>
<th>350</th>
</tr>
</thead>
<tbody>
<tr>
<td>Speed (km/h)</td>
<td>40</td>
<td>59</td>
<td>75</td>
<td>89</td>
<td>84</td>
<td>92</td>
<td>86</td>
</tr>
<tr>
<td>Accel. [raw] (g)</td>
<td>0.31</td>
<td>0.27</td>
<td>0.29</td>
<td>0.31</td>
<td>0.22</td>
<td>0.22</td>
<td>0.17</td>
</tr>
</tbody>
</table>

- From the State Highway network 7 flat curves were selected which had straight approach and departure alignments
- 3 and 4 axle trailers of varying configurations including quad semis in the dataset
- Data captured over one week from GPS instrumented combinations
- Vehicles laden and unladen
- All curve design speeds in North America have SFF less than 0.2
- In New Zealand, all curves with design speeds up to 75 km/h have an SFF of 0.2 or higher
- This suggests the use of a HSO measure in New Zealand is warranted
The HSO during the RTAC study, conceived by the authors because of their involvement in investigating rollover crashes at highway interchanges.

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.

HSO determined at 0.2 g lateral acceleration as the least stable vehicles in the RTAC study were rolling over at 0.25 g.
Billing and Patten used this reference value in assessing four, five and six axle semi trailers fitted with self steering axles, 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.
High speed offtracking – performance measure

- Using a lane width of 3.5 m, a vehicle width of 2.5 m and an 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.
- If the maximum vehicle width in New Zealand was increased to 2.55 m then following the rational above the HSO limit would reduce to 0.325 m with a lane edge distance of 0.15 m or 0.395 m with a lane to edge distance of 0.08 m.
Historical application of HSO in New Zealand

- Not used until 2005 in New Zealand
- Determined at 90 km/h (0.16 g) until 2011
- Reference value subject to debate – values of 0.8 m, more recently 0.5 m, have been used
- Tri-axle semi-trailers with rear self-steer axle had been assessed in an evasive lane change manoeuvre
Revised target values – 393 metre radius

Offtracking versus Lateral acceleration - 393 metre radius curve - Moderate Centring Force

-1400 -1200 -1000 -800 -600 -400 -200 0 200 400

Offtracking (mm)

0 0.05 0.1 0.15 0.2 0.25 0.3 0.35

Lateral acceleration (g)

Moderate - 2+2 (20 tonne)
Moderate - 2+2 (22 tonne)
Moderate - 2+2 (24 tonne)
Moderate - 2+2 (26 tonne)
Moderate - 3+1 (20 tonne)
Moderate - 3+1 (22 tonne)
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A123 (18 tonne)
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Outboard Inboard

Offtracking (mm)

Lateral acceleration (g)
Revised target values – 393 metre radius

Offtracking versus Lateral acceleration - 393 metre radius curve - Moderate Centring Force

- Outboarding
- Inboarding

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Moderate - 2+2 (26 tonne)
Moderate - 3+1 (20 tonne)
Moderate - 3+1 (22 tonne)
Moderate - 3+1 (24 tonne)
Moderate - 3+1 (26 tonne)
A123 (18 tonne)
Conclusions

• Field testing of 2+2 quad-axle semi-trailer combinations with moderate levels of centring force has shown highly non-linear outboard offtracking at lateral accelerations above 0.2 g
• Field testing of 3+1 quad-axle semi-trailer combinations with both moderate and high levels of centring force has shown linear offtracking response right up to the point of rollover at loads of up to 26 tonne
• Computer simulations of the offtracking performance of the field tested combinations confirmed the non-linear trends seen in the high-speed offtracking data recorded during field trials
• The current high-speed offtracking performance measure, adopted from a 1986 Canadian study, has no formal reference value in New Zealand
Conclusions

• A reference high-speed offtracking value of 0.35 m to 0.42 m would be appropriate for use in New Zealand based on the original 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 high-speed offtracking performance used in New Zealand; this could be 0.6 m at 0.25 g or 0.8 m at 0.3 g; this would ensure that combinations with highly non-linear responses were detected.

• All current configuration 2+2 quad semi combinations, exempting air pressure centring combinations with a 20 or 22 tonne axle group limit, would fail these proposed measures.
Recommendations

• All current 2+2 quad-axe semi-trailers should be converted to the 3+1 configuration

• Although computer simulations of the 2+2 APC configuration at 20 and 22 tonnes indicated acceptable performance, the levels of uncertainty associated with the centring force data give rise to a more conservative recommendation

• Minimum requirements for the use of self-steering axles in semi-trailers in New Zealand should be developed and incorporated within a code of practice

• A formal reference value or values should be set for the high-speed offtracking measure; this must take into account New Zealand road designs and the likelihood of laden heavy vehicles exceeding 0.2 g lateral acceleration
Recommendations

• An alternative high-speed offtracking measure that uses a curve radius more typical of those found in the New Zealand road environment should be developed

• The suitability of a curve radius of 212 m and test speeds of 82 km/h and 90 km/h yielding lateral accelerations of 0.25 g and 0.3 g should be investigated

• The level of centring force being produced by self-steering axles used in New Zealand should be provided by the axle manufacturer and based on test data or be tested in New Zealand - it is recommended that the appropriate parts of the Canadian C-dolly test methodology be used to develop a test methodology

• The minimum centring force requirements for 3+1 quad configurations at axle group loads of 22 to 26 tonne should be determined and compared against the range of centring forces produced by self-steering axles available in New Zealand