The Effect of Cross-Sectional Geometry on Heavy Vehicle Performance and Safety

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Executive Summary

The primary objective of this study, done between July 2003 and June 2004, was to determine relationships between road cross-sectional geometry and heavy vehicle performance and then to use these relationships to estimate the effect of road geometry on heavy vehicle crash risk.

The first step was to review the truck crash data to identify where road cross-sectional geometry may have been a factor. A combination of computer simulations and engineering analyses was then used to determine the effect of various road-geometry conditions on heavy vehicle performance. Three vehicles were simulated: a tractor-semi-trailer, a B-train and a truck-trailer rig. Relationships between vehicle performance and crash rates were used to estimate the effect of road cross-sectional geometry on crash risk.

The analysis of the crash data found that:

- Only a very small proportion (1.4%) of truck-involved crashes were reported as having a road cross-sectional geometry feature as a contributing factor.
- However, some 20% of truck-involved crashes were reported as being loss-of-control crashes and it is likely the road cross-sectional geometry will have played a part in many of these.
- Road cross-sectional geometry can also affect the likelihood of occurrence for crashes other than loss-of-control.
- Most (66%) of the loss-of-control crashes occurred while cornering. This is similar to the proportion of rollover crashes that occur while cornering.

Relationships between road cross-sectional geometry characteristics and vehicle performance have been established. Specifically:

- The lateral acceleration required to cause rollover is related to the cross-fall of the road by a simple relationship. (Equation 1)
- The load transfer ratio experienced during a lane-change manoeuvre is related to cross-slope in a more complex way and the effect of cross-slope on stability in a rollover manoeuvre. Also, the effect of cross-slope on a real evasive manoeuvre depends on the specifics of the vehicle, the manoeuvre and the road profile. This effect can be detrimental or beneficial and is, on average not a strong effect.
- All the heavy vehicles simulated had off-tracking sensitivities to cross-slope of around 3 metres/g. Thus, a cross-slope of 0.06 results in a change in off-tracking of approximately 0.18 metres. The sign of the cross-slope determines whether the effect is beneficial or detrimental.
- A sudden drop in pavement elevation resulted in a maximum load transfer of roughly twice the steady-state load transfer. Thus, half of the load transfer was due to the transient. All three of the simulated rigs exhibited this behaviour.

Estimates of the effect of road geometry on heavy vehicle crash rates were made for a number of crash types using previous studies that found relationships between vehicle performance and crash rate. The authors believe this approach of relating road geometry to crash rate via vehicle performance is more insightful than a purely statistical approach.

The key areas where there is potential for significant safety benefits are:

- Banking in curves. A 1% increase in super-elevation could result in a 5% reduction in heavy vehicle loss-of-control crash risk while cornering. This is the largest category of heavy vehicle loss-of-control crashes.
- Seal width and shoulder treatments. Manoeuvres that involve running off the road are the second largest category of loss-of-control crashes. A sudden drop-off at the edge of the seal doubles the steady-state load transfer and thus substantially increases the rollover risk.
- Cross-slope due to camber increases the road width required but the effect is quite small. It is also likely to increase the load transfer during an evasive manoeuvre but the number of crashes resulting from evasive manoeuvres is relatively small.
- The findings should be useful for black spot analysis because the road geometry features that are likely to influence the risk of particular types of crash are identified. This provides a starting point for a more in-depth investigation.

Road design involves trade-offs such as the compromise between drainage and a vehicle's dynamic width when travelling on a straight road. Thus, this report does not specify road-geometric treatments but instead provides the road designer with an appreciation of how certain geometric treatments affect heavy vehicle stability so that the designer can make more informed decisions when designing a road.

Abstract

This study done between July 2003 and June 2004 set out to use relationships between cross-sectional geometry and heavy vehicle performance to estimate the effect of road geometry on heavy vehicle crash risk.

It used computer simulation and engineering analyses to determine these effects with three vehicle types: a tractor-semi-trailer, a B-train and a truck-trailer rig.

The study found the areas with potential for significant benefits to be: banking in curves, seal width and shoulder treatments, and cross-slope due to camber.

The findings should be useful for black spot analysis because the road-geometry features which are likely to influence the risk of particular types of crash are identified.

1. Introduction

1.1 Objective

The primary objective of this study is to determine a relationship between heavy vehicle performance and road geometry. Two road geometry effects are considered:

1. cross-fall, and
2. a sudden step, or change in elevation of the road, on one side of the vehicle. This situation is similar to having the wheels on one side of the vehicle drop off the edge of the pavement.

A secondary objective is to try to estimate the safety impact of these cross-sectional geometries. This was done using the relationships developed between vehicle performance and cross-sectional geometry in conjunction with the results of other studies relating vehicle performance to crash rate.

1.2 Previous Studies

The authors do not know of any other studies relating road geometry to safety via heavy vehicle performance measures. However, there have been several studies to investigate the relationship between road geometry and crash risk using statistics, for example Pasupathy et al. (2000) and Davies (2000). These studies have produced a range of multivariate models with quite different relationships. The authors believe the reasons for these variations are that the relationship between road geometry and crash risk differs between regions and that the parameters that influence crash risk are difficult to characterise. Furthermore, predictor variables that are easy to measure such as seal-width, average annualised daily traffic (AADT), vertical curvature and horizontal curvature are not independent. Thus, there is no consensus about the relationship between road geometry and crash risk and it appears that models developed for roads in one area are often not applicable to roads in other areas.

Davies (2000) looked at the relationship between road geometry and crash risk for all vehicle types. That study found "significant effects due to the horizontal average curvature, difference between maximum and minimum horizontal curvature, and the minimum advisory speed. Small effects were also found for the gradient, direction, sealed carriageway width and annual average daily travel. There are possibly effects associated with surface age, surface type, wet or dry surface, and accident type. There were no significant effects due to cross section slope or vertical curvature."

A study that looked specifically at the relationship between road geometry and heavy vehicle crash risk was Milliken and de Pont (2000). That study used data for heavy vehicle crashes on the State Highway network in New Zealand. They estimated that heavy vehicle crash risk could be reduced by 8% per metre of widening for small increases in road width. This result is backed up by McLean (1997) who estimated a reduction in crash rate of 2% to 2.5% per 0.25 metres of widening. However, there were other predictors such as AADT that had a much stronger relationship with crash rate. These other predictors were not independent of seal width, so it was not possible to confidently attribute an increased crash rate to reduced seal width alone.

Note that the effect of seal width on crash rate is not investigated in this study and the reader may refer to Milliken and de Pont (2000) or McLean (1997) for details of the results mentioned above.

Relationships between heavy vehicle performance and heavy vehicle crash rate have been developed in studies such as Mueller et al. (1999). These relationships are fairly strong so it appears that the relationship between heavy vehicle crash rate and heavy vehicle performance is better understood than the relationship between heavy vehicle crash rate and road geometry. Therefore, a good understanding of how road geometry influences vehicle performance will enable a better understanding of the effect of road geometry on heavy vehicle crash risk.

1.3 Current Practice

Cross-fall refers to the transverse slope of the roadway and represents the combined effect of road camber and super-elevation. Cross-fall is used both to assist drainage and to enable vehicles to travel faster around corners. Typical values of cross-fall are listed in Lay (1998):

Situation	Slope (percent)
grassed shoulders	8
cleared shoulders	6
natural soil surface	6
gravel surface	4
sealed surface	3
asphalt or concrete	2
minimum to avoid ponding	1
minimum for drainage	0.2

Super-elevation is also discussed in Lay (1998).

> "Limits on super-elevation of about 10 percent are imposed by:
>
> a. the inwards rollover (or sideways overturning or lateral stability) of slow-moving high vehicles (outwards rollover is discussed below),
> b. construction problems (e.g. matching with footpath levels),
> c. a tendency for vehicles to track towards the inside of a super-elevated curve, and
> d. the longitudinal distances needed to develop large super-elevations".

Lay (1998) also comments:

> "If snow or ice are present, super-elevations are usually kept below 8 percent."

The shoulder of the road may also be sealed and "on straights, the cross-fall of road shoulders (even where they are sealed) can be up to 2% steeper than the cross-fall of the traffic lanes they flank" (Austroads 1999).

Anecdotal evidence would suggest that vehicles getting so close to the edge of the road that some of the tyres are on the shoulder or even drop off the edge of the seal is relatively important in New Zealand. This is due to a large proportion of narrow, winding roads and the difficulty that drivers have in maintaining their vehicles within their lanes.

2. Method

2.1 Statistical Analysis

The Land Transport Safety Authority (LTSA) maintain a database of all reported vehicle crashes known as the Crash Analysis System or CAS. CAS was interrogated to find all the truck crashes over the last six years. These were then analysed to identify the crashes where road cross-sectional geometry effects were a factor.

The Log Transport Safety Council (LTSC) maintains a database of all log truck rollover crashes. These have been analysed and the results can be compared with the CAS data. There has also been analysis of rollover crashes undertaken in the Netherlands which provides an interesting comparison with the New Zealand data.

2.2 Assessing Vehicle Performance

Computer simulations were used to assess vehicle performance. A multi-body simulation package called Autosim was used for the simulations. A number of the simulations involved standard manoeuvres and standard performance measures including:

- Static Rollover Threshold (SRT), which is the lateral acceleration required to cause rollover.
- Rearward Amplification (RA), which is the ratio of the lateral acceleration of the last body of a combination vehicle to the lateral acceleration of the steer axle on the prime mover during a lane-change manoeuvre. Note that the lane-change manoeuvre that is used is the standard SAE lane-change manoeuvre (SAE 1993).
- Load Transfer Ratio (LTR) which is the proportion of load that transfers from the wheels on one side of the vehicle to the other during a standard lane-change manoeuvre.
- High Speed Transient Off-tracking (HSTO), which is the maximum amount of outboard off-tracking that occurs during a standard lane-change manoeuvre.
- Low Speed Off-tracking (LSO) which is the amount of inboard off-tracking that occurs when negotiating a 90-degree turn at low speed.

Further details of these performance measures are given in Appendix 2.

Three vehicles were used for the computer simulations, a 6-axle tractor-semi-trailer, a 9-axle B-train and a 3-axle truck 4-axle trailer rig. These vehicles are typical of heavy combination vehicles in New Zealand.

Each vehicle was simulated performing the following manoeuvres:

1. a ramp steer to determine its Static Rollover Threshold (SRT)[1]
2. a lane-change manoeuvre
3. an 11.25 metre radius turn at 10kph and 13kph
4. a 373 metre radius steady-state cornering at 55kph, 80kph, 90kph and 100kph
5. a manoeuvre where the vehicle follows a straight path at 100kph and the cross-fall of the road changes suddenly from 0% to 6% so that the wheels on one side of the vehicle drop a short distance.

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[1] SRT is a measure of the lateral acceleration (in g) required for rollover

2.2.1 Cross-slope and the lateral acceleration required for rollover

A simple relationship exists between cross-fall and the lateral acceleration that will cause a vehicle to rollover; if the SRT of a vehicle is σ and the cross-fall is θ (in radians) then the lateral acceleration, a that will cause the vehicle to roll over on a road with a cross-slope of θ is approximately

$$a_{rollover} \triangleq SRT_{effective}g, \qquad \text{Equation 1}$$

where $g=9.81ms^{-1}$ and $SRT_{effective}= \sigma - \theta$. Note that the effect of cross-slope can be beneficial or detrimental to rollover stability depending on the sign of θ.

2.2.2 Cross-slope and load transfer ratio during a lane change

An approximation was used to estimate the effect of cross-slope on the load transfer ratio during a lane-change manoeuvre because the Autosim vehicle models that were available did not respond correctly to cross-slope. For small values of the cross-slope, θ, the effect of cross-slope on load transfer ratio (LTR) during a lane-change manoeuvre is expected to be approximately equal to:

$$LTR_{effective} \triangleq LTR + \frac{\theta}{SRT}, \qquad \text{Equation 2}$$

where

$$LTR \triangleq \frac{F_{z_{left}} - F_{z_{right}}}{F_{z_{left}} - F_{z_{right}}}, \qquad \text{Equation 3}$$

where $F_{z_{left}}$ and $F_{z_{right}}$ are the total loads on the left and right sides of the vehicle[2] .

However, in reality, the effect is more complicated than this. Usually, in the SAE lane-change manoeuvre (SAE 1993), the second steering correction results in the highest lateral acceleration. Thus, for a lane-change manoeuvre to the left, a cross-slope such that the left wheels of the vehicle are higher than the wheels on the right side will usually be advantageous. However, this is only true for cross-slopes up to the value at which the lateral acceleration resulting from the first steering correction exceeds the lateral acceleration resulting from the second steering correction. Moreover, an evasive manoeuvre will often involve a change in cross-slope throughout the manoeuvre. Therefore, the effect of cross-slope on load transfer in a real evasive manoeuvre can be detrimental or beneficial depending on the vehicle, the path and the cross-sectional geometry.

2.2.3 Cross-slope and steady-state off-tracking

An approximation was also used to estimate the effect of cross-fall on steady state off-tracking. This approximation relies on the relationship between the lateral-tyre force generated by a tyre and its slip angle. This approximation is very good for small values of cross-fall where $Cos(\theta) \approx 1$ and $Sin(\theta) \approx \theta$. The lateral force can be due to cross-fall or centripetal acceleration so, rather than simulating cross-fall, speed was adjusted to provide an equivalent amount of centripetal acceleration. Constant-radius cornering simulations were done for the three vehicles at various speeds on a

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[2] Also note that, for the purposes of calculating LTR, a ‘vehicle’ refers to a roll-coupled unit such as a full trailer or an entire B-train combination.

curve of 393 metre radius. Simulations were also done for a slow-speed 90 degree turn of 11.25 metre radius.

2.2.4 The transient effect of a sudden change in cross-slope

When a vehicle encounters a sudden change in pavement height on one side of the vehicle, a transient roll motion is initiated. This situation is similar to that which might occur if one side of a vehicle drops off the carriageway onto the shoulder of the road. This is particularly relevant to New Zealand where the roads are narrow and drivers have difficulty keeping their vehicles within their lanes.

When a vehicle encounters a sudden drop in pavement height on one side of the vehicle, there is a transient response which decays, leaving some steady-state load transfer. The relative importance of the transient effect can be determined by comparing the maximum LTR that occurs during the event with the steady-state LTR. The maximum LTR that occurs during the manoeuvre is

$$LTR_{bump} = \max_t \left(\frac{F_{z_{left}}(t) - F_{z_{right}}(t)}{F_{z_{left}}(t) + F_{z_{right}}(t)} \right), \qquad \text{Equation 4}$$

where t represents time dependence.

Thus, LTR_{bump} represents roughly how close a vehicle comes to rolling over after encountering the bump.

2.3 Safety Implications

The change in vehicle performance due to a change in road geometry was measured in terms of four measures: $SRT_{effective}$, $LTR_{effective}$, off-tracking and LTR_{bump}. The effect of road cross-sectional geometry on crash rates is more difficult to estimate. However, it is likely that a change in $SRT_{effective}$ due to a change in cross-slope will correspond to a change in the probability of a rollover crash. Similarly, it is believed that a change in $LTR_{effective}$ will have an effect on the probability of a rollover or loss-of-control crash. Changes in heavy vehicle off-tracking due to changes in road geometry alter the amount of ‘spare’ space on the road, so this is believed to have an effect on crash rate that is similar to a change in seal width. Likely magnitudes of these effects are discussed in Section 3.4.

3. Results

3.1 Statistical Analysis

The CAS database includes all crashes attended by the police or reported to the police. Crashes are classified in four levels of severity: fatal, serious injury, minor injury and property damage only. All injury crashes (the first three categories) are legally required to be reported to the police while there is no legal requirement to report a property-damage-only crash. Thus, in theory, CAS should include all injury crashes but only a proportion of property-damage-only crashes. In practice, there is a degree of under-reporting at all severity levels but it is much less for more serious crashes. Although the police and the LTSA do make estimates of the level of under-reporting these are little more than a guess. Crashes in CAS are characterised by one of 87 possible movement codes which describe the type of crash. The first letter of the movement code refers to the type of crash and the second letter identifies a particular category within that type. The likely severity of the outcome is not the same for all movement codes. For example, a head-on crash is much more likely to result in a serious injury or fatality than a manoeuvring crash. Because the reporting rate is not constant for all severity levels this distribution of crashes by movement code will not be correct. However, in terms of significant safety gains the highest severity crashes are the most important and these have the highest reporting rates.

The CAS database was queried and there were 16475 heavy vehicle crashes between the start of 1998 and the end of 2003. Of these, 232 (1.4%) had at least one of the following contributing factors listed

- High crown
- Curve not well banked
- Edge badly defined or gave way
- Unusually narrow.

These statistics suggest that geometric effects contributed to a very small proportion of heavy vehicle crashes. However, road geometry is believed to play a part in many more crashes. Although, in most cases, driver error is considered to be the main cause of the crash there are always other contributing factors. Baas (2001) reports from a number of studies that vehicle defects are a contributing factor in many more crashes than indicated by the police reports. The police officer writing the crash report typically identifies the main cause of the crash and does not investigate further. For example, if vehicle A fails to give way to vehicle B and there is a crash, the police do not usually investigate whether vehicle B's brakes are faulty and whether the crash could have been avoided if they were working properly. It is reasonable to expect that where geometry effects are a contributing factor but not easily identified as a major cause, this will not be reported.

Nine of the crash movement codes relate to loss-of-control crashes as shown in Table 3.1. Although these nine codes do not imply a rollover they should include all rollover crashes. Of the 16475 heavy vehicle crashes recorded in the 1998-2003 period there were 3239 heavy vehicle crashes with one of the nine loss-of-control movement codes assigned to them. Thus, 20% of heavy vehicle crashes were loss-of-control crashes of some sort. These are crashes where cross-sectional geometry factors may have contributed.

Table 3.1. Crash codes for loss-of-control crashes.

Movement Code	Type	Category	Numbers of crashes (1998 to 2003)	Percent
AD	Overtaking and lane change	Lost control (overtaking vehicle)	107	3%
AF	Overtaking and lane change	Lost control (overtaken vehicle)	30	1%
BE	Head on	Lost control on straight	151	5%
BF	Head on	Lost control on curve	435	13%
CA	Lost control or off road (straight road)	Out of control on roadway	142	4%
CB	Lost control or off road (straight road)	Off roadway to left	466	14%
CC	Lost control or off road (straight road)	Off roadway to right	192	6%
DA	Cornering	Lost control turning right	1019	31%
DB	Cornering	Lost control turning left	697	22%

Of the loss-of-control crashes some 66% occurred while cornering (movement codes BF, DA and DB) and the vast majority of these (the 53% in movement codes DA and DB) did not involve another vehicle directly.

Crashes other than loss-of-control crashes may also be affected by road geometry. For example, the presence of a relatively flat shoulder could provide a viable escape route to avoid an overtaking head-on crash.

The Log Transport Safety Council (LTSC) maintains a database of all log truck rollover crashes and a recent analysis of these crashes (de Pont et al. 2004) found that of these, 55% related to speed through curves, 21% to running onto the verges and off the edge of the roadway, and 6% to evasive manoeuvres. Hoogvelt et al. (1997) in a study of rollover crashes in the Netherlands found that, according to the police reports, 61% were related to curves and speed through curves, 26% to running onto the verges and 10% to swerving (evasive manoeuvres). Given the enormous differences (in vehicle configuration, terrain and road network) between New Zealand log transport operations and commercial vehicle operations in the Netherlands, these proportions are remarkably similar. These crash causes provide an insight into which performance measures are likely to be most important in terms of crash risk. They should be kept in mind when interpreting simple statistical correlations. The findings of the analysis of the CAS data are also consistent with these proportions.

3.2 Computer Simulations

The results of the computer simulations are shown in Table 3.2.

Table 3.2: Summary results for the simulations.

Performance measure	Tractor-semi-trailer	B-train	Truck-trailer
SRT	0.30	0.38	0.44
(Rollover unit)	1 of 1	1 of 1	1 of 2
RA	1.35	1.92	2.27
HSTO	0.12	0.20	0.32
LTR	0.44	0.30	0.92
LSO (10kph)	3.35	3.30	2.37
LSO (13kph)	3.22	3.11	2.19
HSO (55kph)	0.04	0.10	0.12
HSO (80kph)	0.22	0.34	0.34
HSO (90kph)	0.32	0.46	0.46
HSO (100kph)	0.44	0.61	0.60
$\mathrm{LTR}_{\mathrm{bump}}$	0.74	0.67	0.81
$\mathrm{LTR}_{\mathrm{bumpfinal}}$	0.35	0.306	0.35

To cover a range of scenarios, the simulated vehicles had a range of SRT values and three different types of vehicle were used.

3.3 Road Geometry and Vehicle Performance

3.3.1 Cross-slope and rollover

The SRTs (for a flat road) for each of the simulated vehicles are shown in Table 3.2. If a curve is designed with a favourable cross-slope of, say, 6% then the effective SRT will be:

$$SRT_{effective} = SRT + 0.06. \quad \text{Equation 5}$$

The SRT values of the vehicles that were simulated ranged from 0.3 to 0.44. Therefore, for these vehicles, 13 to 20 percent greater lateral acceleration is required to cause rollover on a curve with 6 percent cross-fall in the favourable direction. Similarly, if a cross-slope of 6% is imposed in the unfavourable direction, the effective SRT is reduced by the same magnitude.

3.3.2 Cross-slope and load transfer ratio during a lane change

The load transfer ratios for the simulated vehicles are shown in Table 3.2. As expected, the LTR for the truck-trailer rig is considerably worse than the LTRs for the fully roll-coupled vehicles. This disparity between these vehicle types is typical.[3] The effect of cross-slope on the load transfer during an evasive manoeuvre was discussed in Section 2.2.2. The effect can be detrimental or beneficial depending on the vehicle, the cross-slope and the path of the manoeuvre. Thus, the effect is not clearly detrimental or clearly beneficial.

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[3] Until recently, due to their poor dynamic-performance at highway speeds, non-roll-coupled vehicles were speed limited to 80km/h whereas the speed limit for roll coupled articulated vehicles was 90km/h. It is now 90km/h for all heavy vehicles.

3.3.3 Cross-slope and steady-state off-tracking

It is well known that low-speed (inboard) off-tracking reduces with speed, and high-speed (outboard) off-tracking increases with speed. This is due to the vehicles' tyres having to develop a sufficiently large slip angle to provide the necessary cornering force which in turn results in the lateral acceleration during cornering.

The gradient of the line of best fit in Figures 3.1 and 3.2 will be referred to as the 'off-tracking sensitivity to cross-slope' for each vehicle. It is interesting to note that the gradients of these off-tracking sensitivities to cross-slope all roughly equal. Thus, although the vehicles have different absolute off-tracking values, the absolute effect of lateral acceleration on off-tracking is similar between the vehicles.

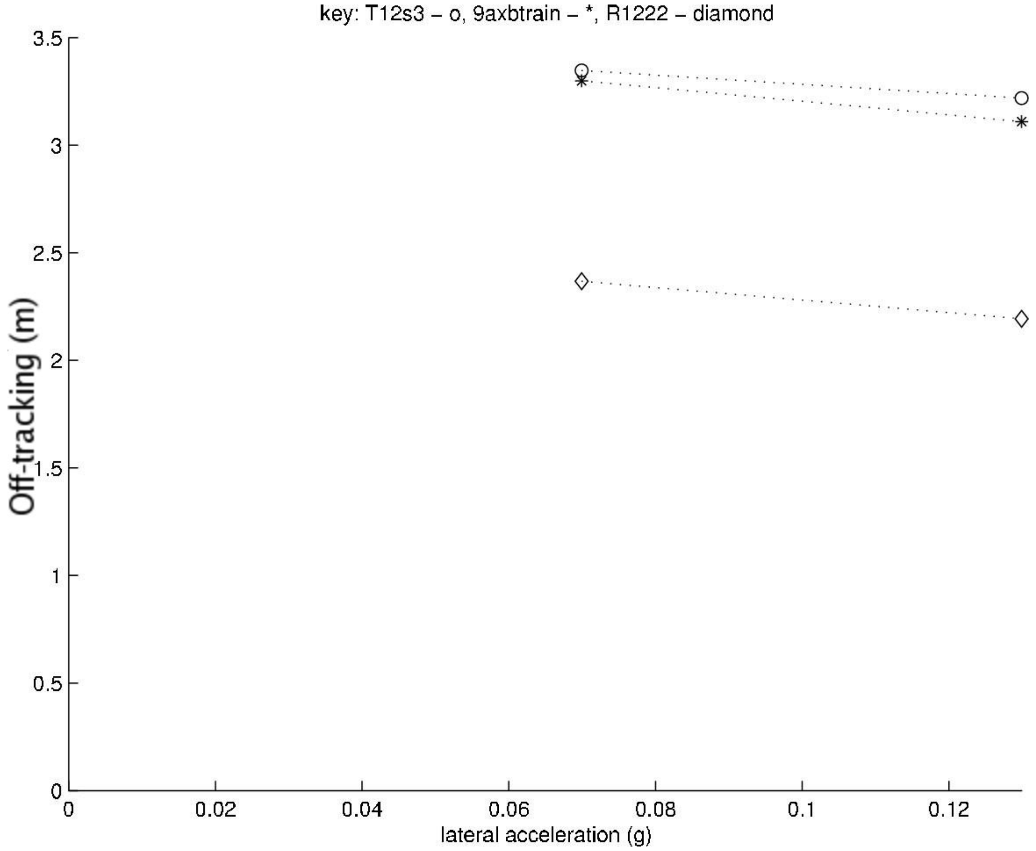

Figure 3.1: Lateral acceleration versus low speed off-tracking for the tractor-semi-trailer, the B-train and the truck-trailer.

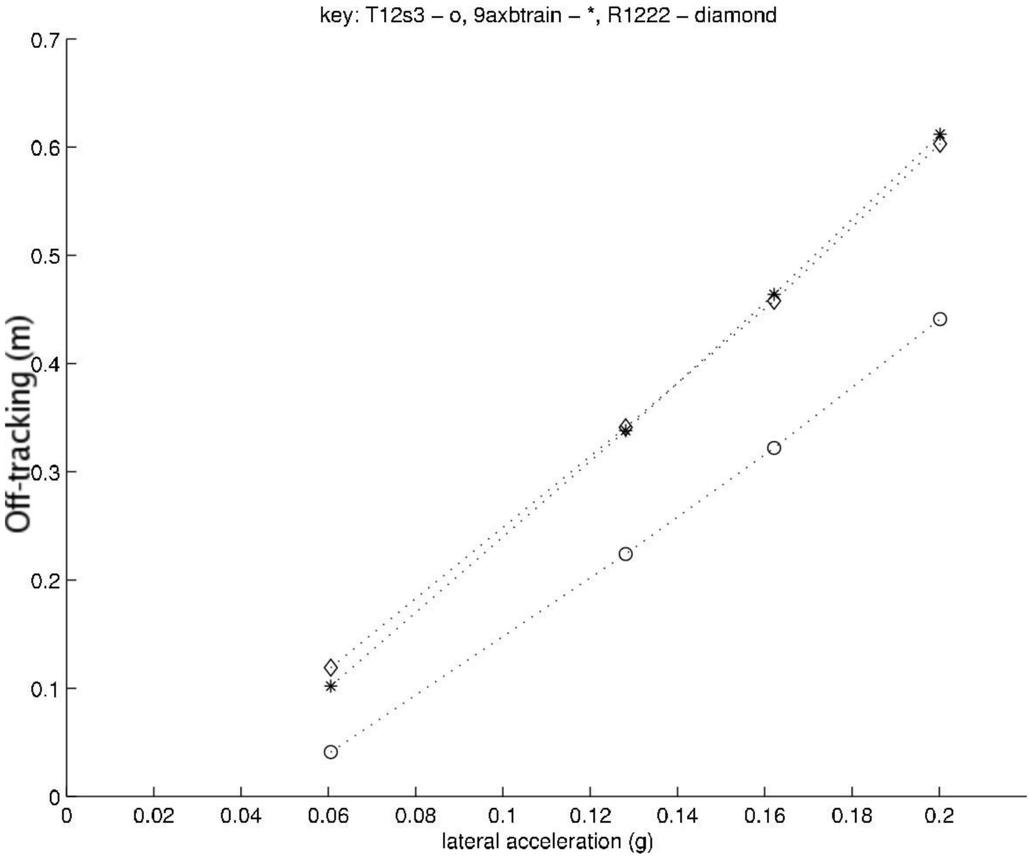

Figure 3.2: Lateral acceleration versus high speed off-tracking for the tractor-semi-trailer, the B-train and the truck-trailer.

The off-tracking sensitivities to cross-slope for the data shown in Figures 3.1 and 3.2 are between 2.85 and 3.65 metres/g for the three vehicles that were simulated. An example is useful to help the reader to get an appreciation for the effect of cross-slope on off-tracking. Consider a vehicle with an off-tracking sensitivity to cross-slope of 3 metres/g. Suppose the vehicle has inboard off-tracking of 1 metre when travelling around the curve at a certain speed. A change in cross-fall on the bend from zero to 0.06 (where the outside of the bend is higher than the inside) would result in off-tracking of 1.18 metres. So, the amount of 'spare' space in this vehicle's lane is reduced by 0.18 metres. A similar concept is used in the Australian Performance Based Standards (PBS) project, where the amount of swept space by a vehicle travelling along a typical straight road is referred to as the 'dynamic width' of the vehicle.

3.3.4 Load transfer ratio & sudden change in cross-slope of the road

Plots of the sums of wheel loads on the right side of each vehicle when subjected to a sudden drop in elevation are shown in Figure 3.3. (p19)

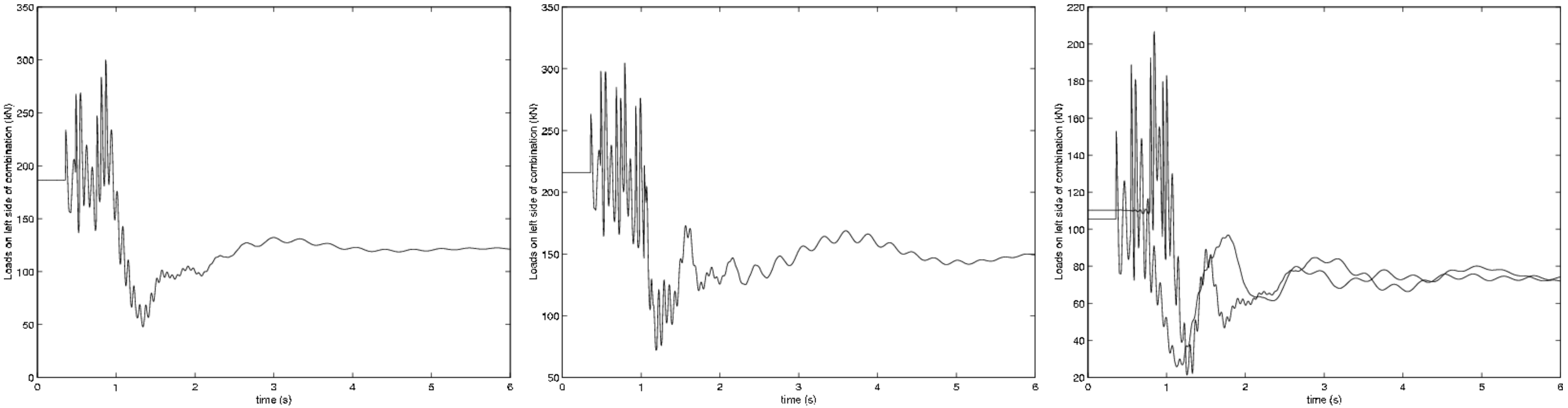

Figure 3.3: Sum of wheel loads on the right sides of the three vehicles during a sudden drop in elevation on one side of the road. Plots are for the tractor-semi-trailer, the B-train and the truck-trailer, respectively.

Notice that, as each axle encounters the drop, there is a spike in the wheel load. It is interesting that the steady-state change in wheel load is approximately half of the maximum change in wheel load for each of the vehicles. This means that the transient roll motion introduced by the suddenness of the change in cross-slope is responsible for about half of the peak load transfer. Therefore, a sudden change in elevation on one side of the vehicle is significantly more likely to cause rollover than a gradual change. Also note that there are two plots for the truck-trailer rig as the truck and the trailer are not roll-coupled and therefore constitute separate vehicles.

The authors were surprised that the fully roll-coupled combinations responded in a similar way to the truck-trailer rig after encountering the drop in elevation on one side of the vehicle. It had been expected that a greater proportion of the load transfer on the truck-trailer rig would be due to the transient effect since the truck-trailer is actually comprised of two shorter vehicles.

3.4 Safety Implications

Vehicle simulations were used to estimate the effect of road geometry on vehicle performance. The effect of vehicle performance on crash risk, however, is more difficult to estimate. This is because crash risk depends on a number of other factors such as the environment and driver behaviour. For example, poor SRT is likely to be less problematic in a location with a lot of straight roads than in a mountainous area with winding roads.

In several of the following sections we use relationships determined by Mueller et al. (1999) in a statistical study which related performance measures to crash rates. However, the crashes analysed in this study were all rollover and loss-of-control crashes in New Zealand over a time period. At the time the study was done it was not possible to identify whether the causes of these crashes were likely to be related to the performance measure being considered.

The statistical analysis presented in Section 3.1 does provide some insight into which types of crash are most predominant and hence which aspects of vehicle performance and cross-sectional geometry are likely to be most important from a safety point of view.

3.4.1 Cross-slope and rollover crashes

Mueller et al. (1999) reported an observed relationship between vehicle performance and rollover and loss-of-control crash rates. The heuristic relationship between SRT and relative rollover and loss-of-control crash rate, f_{SRT}, was

$$f_{SRT} = -63.2SRT^3 + 127SRT^2 - 85SRT + 19.5 \qquad \text{Equation 6}$$

and is shown in Figure 3.4.

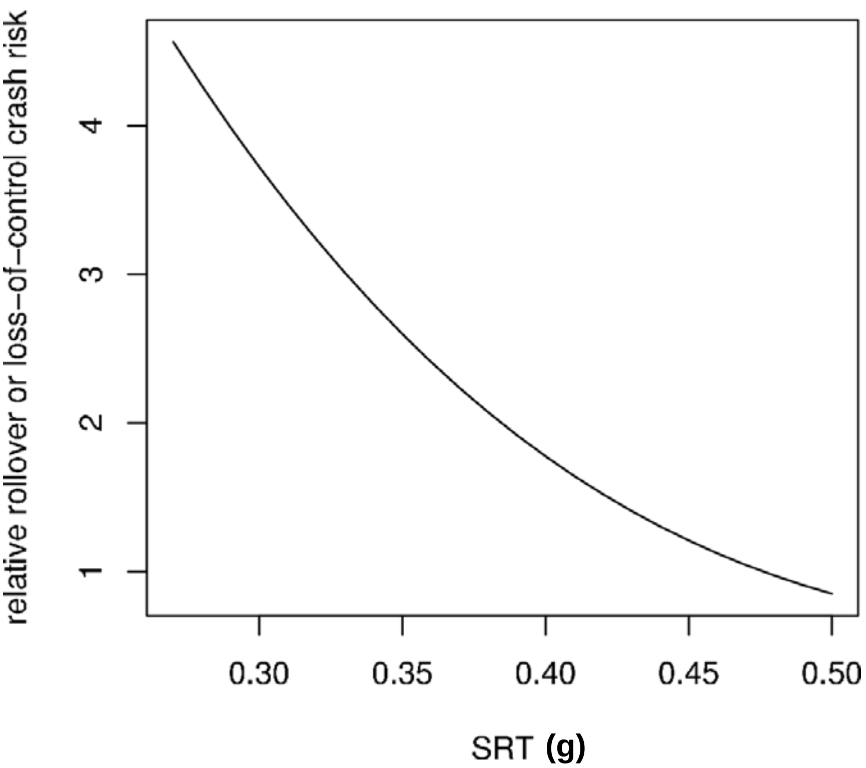

Figure 3.4: Relationship between SRT and heavy vehicle rollover or loss-of-control crash rate.

In principle, drivers are expected to drive in a way that is appropriate for the performance of the vehicle. So, a vehicle with a poor SRT should be driven more slowly around bends than a vehicle with a better SRT. However, there is still a strong relationship between SRT and rollover and loss-of-control crashes, which suggests that drivers of less stable vehicles are either insufficiently aware of the reduced cornering capability of their vehicles or they do not modify their driving behaviour sufficiently.

It is believed that cross-slope and super-elevation affect the probability of a rollover or loss-of-control crash. It is not uncommon for adverse cross-slope to be identified as a factor when accident black spots are investigated. It seems plausible that a relationship similar to that shown in Figure 3.4 will hold for the relative rollover and loss-of-control crash rate where cross-fall is accounted for by considering $SRT_{effective}$ rather than SRT. Thus, the estimated relative rollover and loss-of-control crash rate, $f_{SRT_{effective}}$ is:

$$f_{SRT_{effective}} = -63.2SRT^3_{effective} + 127SRT^2_{effective} - 85SRT_{effective} + 19.5. \qquad \text{Equation 7}$$

If this relationship holds, the effect on relative rollover and loss-of-control crash risk for changes in cross-slope is as shown in Figure 3.5. As expected the greatest gains (or losses) are for the poorest performing vehicles.

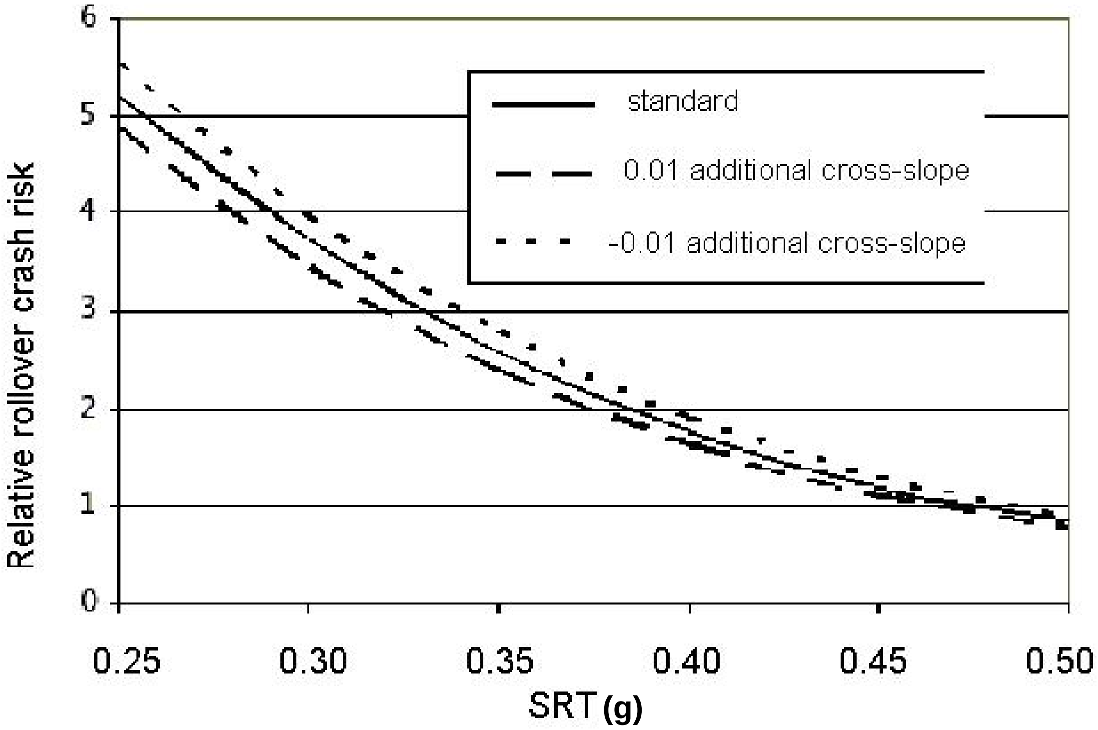

Figure 3.5: Estimated SRT versus relative rollover and loss-of-control crash rate for different amounts of crossfall.

Mueller et al. (1999) estimated the distribution of SRT for the New Zealand heavy vehicle fleet which is reproduced in Figure 3.6. To estimate the potential overall crash risk reduction from, say, a change of 0.01 in super-elevation in curves we need to apply a weighting reflecting the proportions of the fleet to the gains illustrated in Figure 3.6. Applying this indicates that a 0.01 (i.e. 1%) change in cross-slope would lead to a 5% change in rollover and loss-of-control crash risk. It should be noted that the fleet distribution of SRT is based on data obtained in the late 1990s. Since then New Zealand has introduced a minimum SRT requirement for most large heavy vehicles and so the poorest performing vehicles (those with an SRT less than 0.35g) should have been upgraded to achieve an SRT of more than 0.35g. That is, the vehicles in the bottom two bins of the histogram (Figure 3.6) will have been redistributed into the higher bins. This does not have a great impact on the calculated crash rate change.

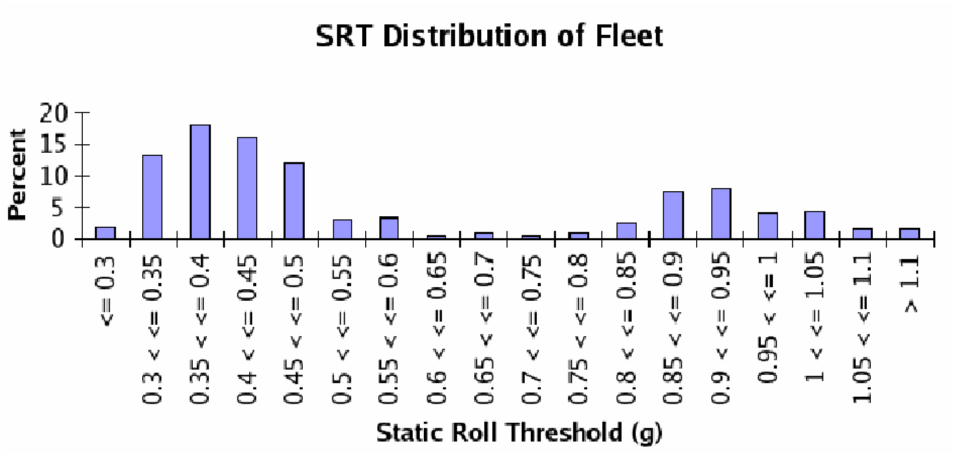

Figure 3.6: Estimated SRT distribution within the heavy vehicle fleet in New Zealand in 1999.

However, there are a number of others factors that exist that were not taken into account in this rather simple analysis. The first and most important is driver behaviour. The analysis implicitly assumes that the benefit of the change in effective rollover stability of the vehicle is translated into a change in crash risk. But, if curves are favourably banked, the advisory speed values for the curves increase and it is likely that some drivers, at least, will increase their speed to take advantage of the additional stability. The 5% crash risk reduction for a 1% increase in cross-slope could therefore be regarded as an upper limit. A possible lower limit can be obtained by assuming that drivers change their speed to utilise all of the change in risk and that the crash risk is unaffected by change in cross-slope. This is not very likely to be the case. The remedial treatment at accident black spots does, in some instances, involve eliminating adverse road camber and this does work to reduce crash rate which indicates that changes in driver behaviour do not eliminate all the benefits.

The report by Mueller et al. (1999) used statistical analysis to relate rollover and loss-of-control crash rate to vehicle performance. They did not consider whether the individual crashes were attributable to the aspect of performance characterised by the performance measure being analysed. For example, SRT relates to the steady speed cornering stability of the vehicle and also affects the stability in evasive manoeuvres. A crash where the driver falls asleep, runs off the road and rolls the vehicle would still have been included in the crash data analysed even though SRT was almost certainly not a factor. Increasing the effective SRT by increasing the super-elevation affects the rollovers caused by excessive speed through curves which comprise some 55-60% of the total rollover crashes. Other types of rollover crash should not be affected by this type of road geometry change.

3.4.2 Transverse road slope and rollover and loss-of-control crashes resulting from evasive manoeuvres

If we take the same approach as the previous section we can estimate a relationship between relative rollover and loss-of-control crash risk and $LTR_{effective}$. This relationship is shown in Figure 3.7.

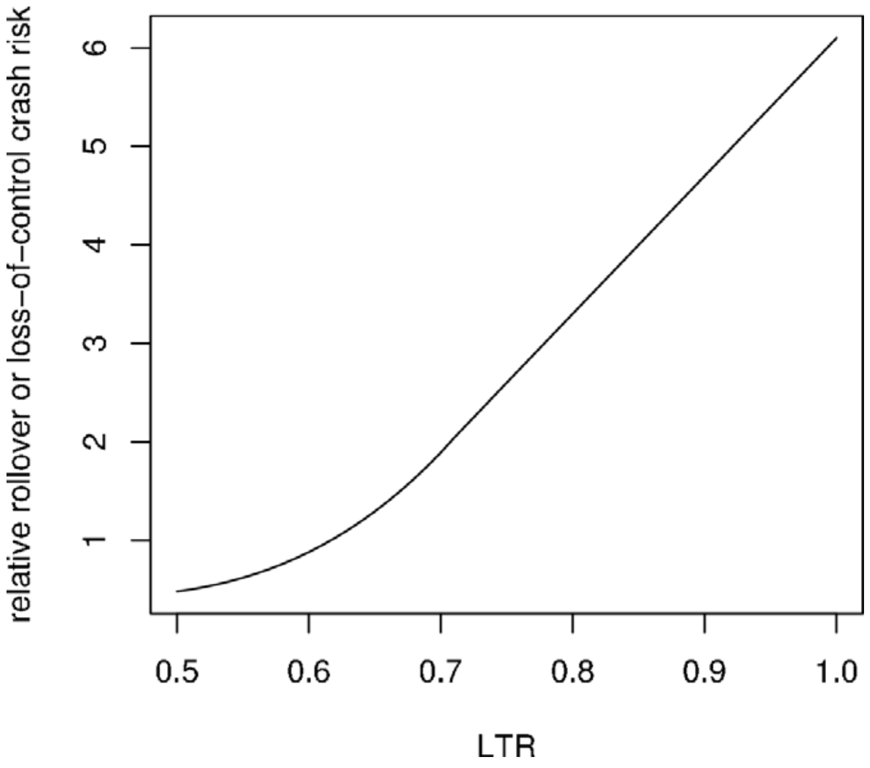

Figure 3.7: Relationship between LTR and heavy vehicle rollover or loss-of-control crash rate.

This would suggest, for example, that for the truck-trailer configuration modelled a 1% change in cross-slope would lead to a 7% increase in crash risk while for the tractor-semi and B-train there would be little change. However, this is likely to be incorrect. The relationship between LTR and crash risk developed by Mueller et al. (1999) is based on all the rollover and loss-of-control crashes recorded over a three year period. It did not distinguish speed-through-curve crashes from evasive manoeuvres crashes and run-off-the-road crashes. (With the data available at the time this was not possible.) Based on the log truck crash data and the Dutch study by Hoogvelt mentioned earlier, it is very likely that fewer than 10% of these crashes were the result of evasive manoeuvres. On the other hand, for a given vehicle configuration, LTR and SRT are correlated. Thus it is likely that the relationship between LTR and crash risk is a result of the correlation between SRT and LTR rather than a direct reflection of the effect of LTR.

Overall, evasive-manoeuvre induced rollover crashes are a small proportion of the total number of rollover and loss-of-control crashes. A small change in risk will have only a very small impact on overall crash rates. While increased cross-slope can have an impact on LTR and is likely to alter the risk of rollover during an evasive manoeuvre it is difficult to quantify the size of this effect with any confidence. It appears that the effect is likely to be negligible for roll-coupled vehicles (tractor-semis and B-trains) because their underlying LTR is low and the main impact will be on the poorer performing truck-trailer combinations.

3.4.3 Transverse road slope and loss-of-control crashes resulting from running off the road

Cross-slope affects the amount of off-tracking a vehicle experiences when it travels around a curve with a certain radius of curvature at a certain speed. The difference between the distance from the edge of the seal to the centre-line of the road and the swept width of the vehicle is the amount of ‘spare’ space on the road. The effect on crash risk, for seal-width related crashes, of a change in the ‘spare’ space on the road is not known. However, the authors suspect that the effect will be similar to a change in seal width, which also changes the amount of ‘spare’ space on the road.

Milliken and de Pont (2000) estimated the average effect of small changes in road width on crash risk to be 8% per metre of road widening for possibly-seal-width-related crashes on state highways in New Zealand. This finding is backed up by McLean (1997). Since off-tracking increases the amount of road width required by a vehicle, it is proposed that the safety effect of cross-slope in a curve, after allowing for changes in the effective SRT, is equivalent to altering the width of the road by an amount equal to the change in off-tracking.

Road roughness also contributes to off-tracking and the combination of cross-slope and road roughness means that the swept width of a vehicle travelling on a straight road is greater than the width of the stationary vehicle. In this instance, the swept width of the vehicle is known as the ‘dynamic width’. The difference between seal width and the dynamic width of a vehicle (i.e. the amount of spare space on one side of the road) is of particular importance for cyclists and vehicles parked on the side of the road. Between 1998 and 2003 there were 193 crashes involving trucks and cyclists, 73 percent of which were either overtaking crashes or crossing/turning crashes. This compares to 5522 cycle crashes in that period.

3.4.4 A sudden drop in elevation on one side of the road

The elevation change covered in this section may be the result of an irregularity in the road surface, or where the vehicle’s wheels drop off the roadway onto a soft shoulder or grass berm either because of insufficient road space or driver error. The LTSC crash database (de Pont et al. 2004) and the study by Hoogvelt et al. (1997) suggest that 20 to 25 percent of rollover crashes fall into this category. There is additional anecdotal evidence to suggest that having some of the wheels on one side of a heavy vehicle drop off the edge of the road has been a factor in a number of rollover crashes. In some cases the wheels have not dropped off the edge but merely gone too close to it and the edge of the seal has broken leading to the crash. Cases have also been reported where a vehicle rolls over after the wheels have dropped off the edge of the road and then come back onto the road again.

The simulation results indicate that all three vehicle configurations were adversely affected in a similar way by a sudden drop on one side of the vehicle with the transient effect being approximately double the steady state effect. The real-life situation, however, is more complicated than the simple performance measure scenario. The driver is likely to apply steer inputs to get the vehicle back on the road and these may be more or less gentle, the tyres may slide sideways on the shoulder and the cross-slope on the shoulder may become steeper as the vehicle moves further left. It is reasonable to postulate that if the elevation change relates to an irregularity in the road surface but the road width itself is adequate the increased safety risk will be relatively small. If the elevation change is associated with the vehicle’s wheels leaving the edge of the road surface, then we have the situation analysed by Milliken and de Pont and we can expect a crash reduction of the order of 8% per metre of road widening. The effect of not widening the roads but of, say, increasing shoulder width or reducing the cross-fall of the shoulders is expected to be somewhere between 0 and 8% per metre of extra 'spare space'.

Figure 3.8: Photograph of a poorly designed piece of road.

Figure 3.8 shows a section of road where several rollover and loss of control crashes have occurred. The seal is narrow, the sealed shoulder is minimal and the seal becomes very steep on the shoulder. Furthermore, the grass beside the road is significantly lower than the seal and steeply banked.

The severity of a sudden change in elevation on one side of a vehicle can be evaluated by estimating the maximum load transfer that would occur for a particular vehicle on such a road. Furthermore, the magnitude of the vertical change in elevation on one side of the road that will cause rollover can be estimated. Consider an example of a vehicle with a track width of 1.5 metres and an SRT of 0.35. Suppose the vehicle encounters a bump of size *b*. Since it has already been established that, regardless of vehicle type, the transient effect is roughly the same magnitude as the steady-state load transfer on a straight road, a change in elevation that causes an angle of 0.35/3 or 0.175 radians would be sufficient to cause wheel lift-off. Since the track width is 1.5 metres, the vertical drop is 260 millimetres. Note that this example is for a straight, level road where there is a sudden drop in elevation and the vehicle is travelling at highway speed. A bump will have a very different effect from a drop under these circumstances due to the fact that wheels may leave the ground when going over a drop and other non-linearities become important for relatively large disturbances. Also note that, on a curve where there is already a certain amount of load transfer, the change in elevation on one side of the vehicle that is required for wheel lift-off is reduced accordingly.

4. Discussion

The effects of various cross-sectional geometry characteristics on vehicle performance have been determined and using relationships between vehicle performance and crash risk, the implications for safety have been estimated. In this section we discuss how these findings might be used.

Broadly speaking the interactions between cross-sectional geometry and vehicle performance affect two key safety elements. These are the stability of the vehicle and the road space required. Road space is characterised by seal width and by lane width but the relationship between the two is not as simple as might be expected. The discussion will begin by reviewing this relationship and how it interacts with vehicle performance and safety.

When considering the effects of cross-sectional geometry on vehicle performance we need to distinguish between the situation in curves and the situation generally. There are factors which apply only in curves, while the factors that apply on straight roads usually also apply to curves. These two situations are considered separately.

4.1 Seal Width and Lane Width

Seal width is the width of the roadway that is paved. Lane width is the width of the lanes as marked. As noted earlier, MacLean (1997) found a relationship between seal width and safety which basically said that increasing seal width improves safety. Milliken and de Pont (2001) noted that a number of researchers have found relationships between lane width and safety which suggest that there exists an optimum lane width and thus that either increasing the lane width above the optimum or reducing it below the optimum will increase crash risk. This optimum lane width is about 3.5m which is what Transit New Zealand specifies as the required lane width for a state highway.

It might be expected, therefore that provided the seal width on a two-lane road was greater than 7m, the lanes would be 3.5m wide while if the seal width was less than 7m the lane widths would be half the seal width. Milliken and de Pont (2001) measured seal width and lane width at more than 300 sites on the State Highway network and found that although there was some evidence of this relationship it certainly does not apply universally. In many cases the lane width on opposite sides of the road at the same location differed substantially and the seal width data for the site recorded in the RAMM (Road Assessment & Management System) database did not match the measured values.

Lane width is not directly related to vehicle performance although it does provide important cues for the driver. Seal width on the other hand is directly related. For example, suppose that for a given curve at a given speed the off-tracking characteristics of a vehicle mean that it requires a road width of 5m. If the seal width through the curve is 11m and the centreline runs down the centre the vehicle has 5.5m of seal available and thus has 0.5m of spare space. It should make no difference to the safety risk whether the fog line is at 3.5m from the centreline or 4.5m. It is possible to establish relationships between seal width and vehicle performance and then estimate the safety impacts. It is not possible to take the same approach to lane width.

4.2 Curve-Specific Factors

From the CAS data some 66% of loss-of-control crashes occurred in curves, with 53% being loss-of-control while cornering. Thus these are a significant proportion of the total loss-of-control crashes. The effective rollover stability of trucks travelling through curves can be increased by increasing the super-elevation (i.e. banking the corner). From the results of Section 3.4.1 we see that a 1% change in cross-slope would change the rollover crash rate by up to 5%. The actual gains may be less if drivers increase speed to offset the stability gain from the banking. However, increasing the super-elevation increases the amount of inboard off-tracking of vehicles through the curve. For large-radius high-speed curves, vehicles tend to have outboard off-tracking and so increasing the amount of inboard off-tracking actually reduces the road width required by the vehicle, but vehicles travelling slowly through the same curves will already have inboard off-tracking and so increasing super-elevation will mean that the vehicle requires more road width. For lower-speed smaller radius curves increased super-elevation will mean that all heavy vehicles require increased road width. As shown in Section 3.3.3 the change in off-tracking from a change in cross-slope is between 2.85m/g and 3.65m/g depending on the vehicle type. A 1% change in super-elevation will therefore increase the road width required by about 40mm which is negligible. A larger change in cross-slope would result in a significant increase in road width required. If the additional road width was not provided the crash rate would increase as discussed in Section 3.4.2, i.e. 8% per metre of road width. This effect is very much smaller than the stability gains and can be ignored.

The other area where vehicle performance and cross-sectional geometry interact on curves is the additional road width required to accommodate the vehicle off-tracking while cornering. However, the cross-sectional property (i.e. road width) does not affect the vehicle's performance per se and so this effect is outside the scope of this study. Milliken (2001) presents some simple formulae for estimating the road width requirements for different vehicle configurations for a given curve radius. These formulae can be used to assess whether the seal width available is adequate for the worst case vehicles and the safety improvements from widening can be estimated using MacLean's (1997) result i.e. 8% crash rate reduction per metre of road widening.

4.3 General Factors

As noted above, cross-sectional geometry properties affect vehicle stability and road width requirements. These two factors do interact. A driver has a better chance of recovering from a loss of control if he or she has more road width available. Conversely leaving the seal surface because of inadequate seal width is less likely to lead to a loss-of-control event if the shoulder is level with the road surface and does not drop away suddenly.

If an evasive manoeuvre involves the vehicle crossing the centreline of the road, it is likely that the cross-slope due to road camber will worsen the vehicle's dynamic performance on both turns; the greater the camber the greater the degradation. In Section 3.4.2 it was estimated that the increase could be at much as a 7% change in crash risk per 1% change in camber but it was noted that there are relatively few crashes recorded for this type of manoeuvre.

Increasing cross-slope increases the road width required by heavy vehicles. This is equivalent to reducing the seal width. Every 1% increase in cross-slope results in approximately 40mm of additional road width required which in turn results in a 0.32% increase in crash risk. Thus the effect is quite small. If there is a sudden drop off at the edge of the road the risk of loss-of-control or rollover is substantially increased (the dynamic load transfer is double). However combining these effects is not straightforward because the relationship between crash risk and road width is an average figure and already includes both favourable and unfavourable shoulder conditions.

4.4 Applying the Results

Most of the crashes where road cross-sectional properties affecting vehicle performance are possibly a factor occur while cornering. Thus the biggest safety gains are achievable in treating the cross-sectional properties in curves. Within curves the biggest safety gains comes from banking the curve to improve vehicle stability. It is also important to ensure that the seal width is adequate to accommodate the vehicle off-tracking.

The other major opportunity for using these findings is in analysing black spots. By analysing the specific crashes that have occurred it should be possible to determine what aspects of vehicle performance were important in causing the crashes. The cross-sectional geometry factors that affect those vehicle performance characteristics can be reviewed and appropriate remedial action taken.

5. Conclusions

The analysis of the CAS crash data base found that:

- Only a very small proportion (1.4%) of truck-involved crashes were reported as having a road cross-sectional geometry feature as a contributing factor.
- However, some 20% of truck-involved crashes were reported as being loss-of-control crashes and it is likely the road cross-sectional geometry will have played a part in many of these.
- Road cross-sectional geometry can also affect the likelihood of occurrence for crashes other than loss-of-control.
- Most (66%) of the loss-of-control crashes occurred while cornering. This is similar to the proportion of rollover crashes that occur while cornering.

Relationships between road cross-sectional geometry characteristics and vehicle performance have been established. Specifically:

- The lateral acceleration required to cause rollover is related to the cross-fall of the road by a simple relationship. (Equation 1)
- The load transfer ratio experienced during a lane-change manoeuvre is related to cross-slope in a more complex way and the effect of cross-slope on stability in a rollover manoeuvre. Also, the effect of cross-slope on a real evasive manoeuvre depends on the specifics of the vehicle, the manoeuvre and the road-profile. This effect can be detrimental or beneficial and is on average not a strong effect.
- All the heavy vehicles simulated had off-tracking sensitivities to cross-slope of around 3 metres/g. Thus, a cross-slope of 0.06 results in a change in off-tracking of approximately 0.18 metres. The sign of the cross-slope determines whether the effect is beneficial or detrimental.
- A sudden drop in pavement elevation resulted in a maximum load transfer of roughly twice the steady-state load transfer. Thus, half of the load transfer was due to the transient. All three of the simulated rigs exhibited this behaviour.

Estimates of the effect of road geometry on heavy vehicle crash rates were made for a number of crash types using previous studies that found relationships between vehicle performance and crash rate. The authors believe this approach of relating road geometry to crash rate via vehicle performance is more insightful than a purely statistical approach. The key areas where there is potential for significant safety benefits are:

- Banking in curves. A 1% increase in superelevation could result in a 5% reduction in heavy vehicle loss-of-control crash risk while cornering. This is the largest category of heavy vehicle loss-of-control crashes.
- Seal width and shoulder treatments. Manoeuvres that involve running off the road are the second largest category of loss-of-control crashes. A sudden drop-off at the edge of the seal doubles the steady-state load transfer and thus substantially increases the rollover risk.
- Cross-slope due to camber increases the road width required but the effect is quite small. It is also like to increase the load transfer during an evasive manoeuvre but the number of crashes resulting from evasive manoeuvres is relatively small.

- The findings should be useful for black spot analysis because the road-geometry features that are likely to influence the risk of particular types of crash are identified. This study provides a tool which can be used as a starting point for a more in-depth black-spot investigation.

Road design involves trade-offs such as the compromise between drainage and a vehicle's dynamic width when travelling on a straight road. Thus, this report does not specify road-geometric treatments but, instead, provides the road designer with an appreciation of how certain geometric treatments affect heavy vehicle stability so that the designer can make more informed decisions when designing a road.

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Appendices

Appendix 1: Simulations For All Vehicles

This appendix shows plots of the pertinent parameters for the vehicle simulations that were done for this study. Figure A1.1 shows the load on the right side of each vehicle for a ramp steer. This manoeuvre was used to determine the SRT, or the lateral acceleration (in g) at which each vehicle rolls over. Note that the third plot is only for the trailer of the truck-trailer rig since the trailer rolled first.

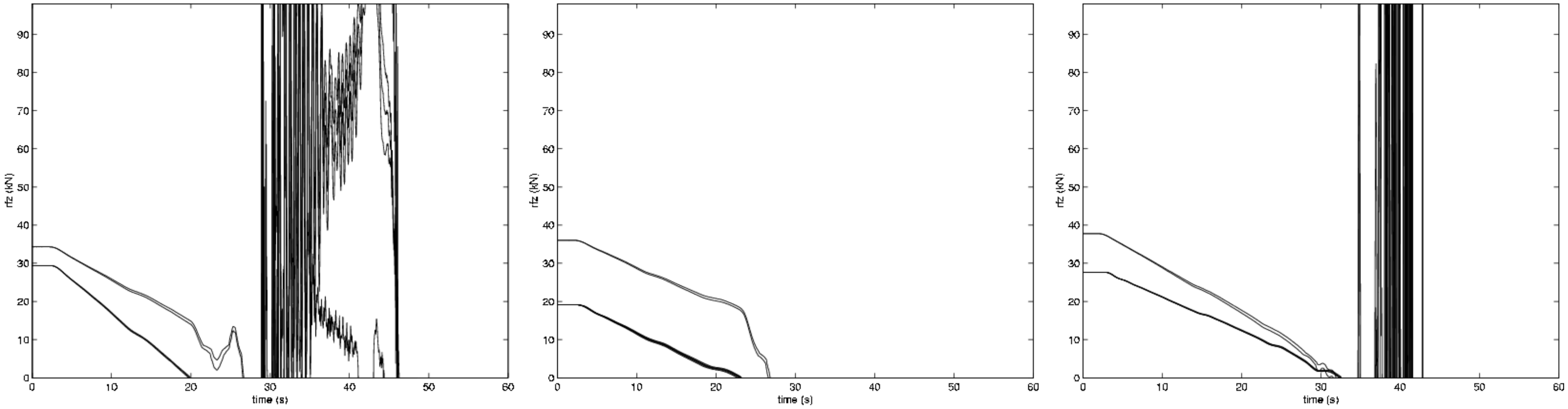


Figure A1.1: Load on wheels on the right side of each vehicle for ramp steer. The plots are for the tractor-semi-trailer, the B-train and the truck-trailer, respectively.

Figures A1.2 to A1.4 show the results of a standard SAE lane-change manoeuvre. Each plot shows results for the tractor-semi-trailer, the B-train and the truck-trailer rigs, respectively.

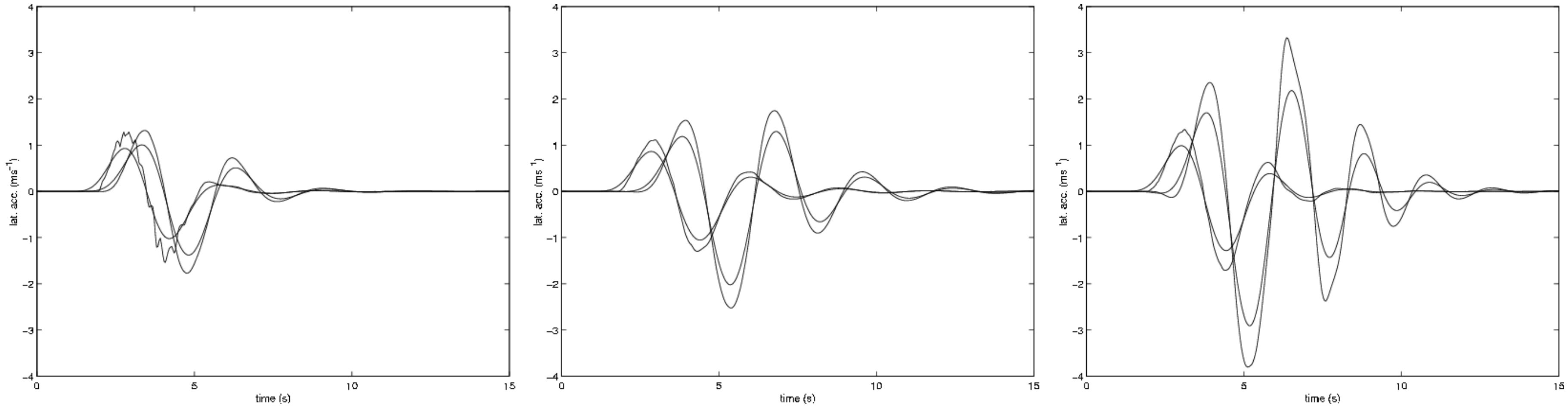


Figure A1.2: Lateral acceleration during lane-change simulations for the tractor-semi-trailer, the B-train and the truck-trailer, respectively.

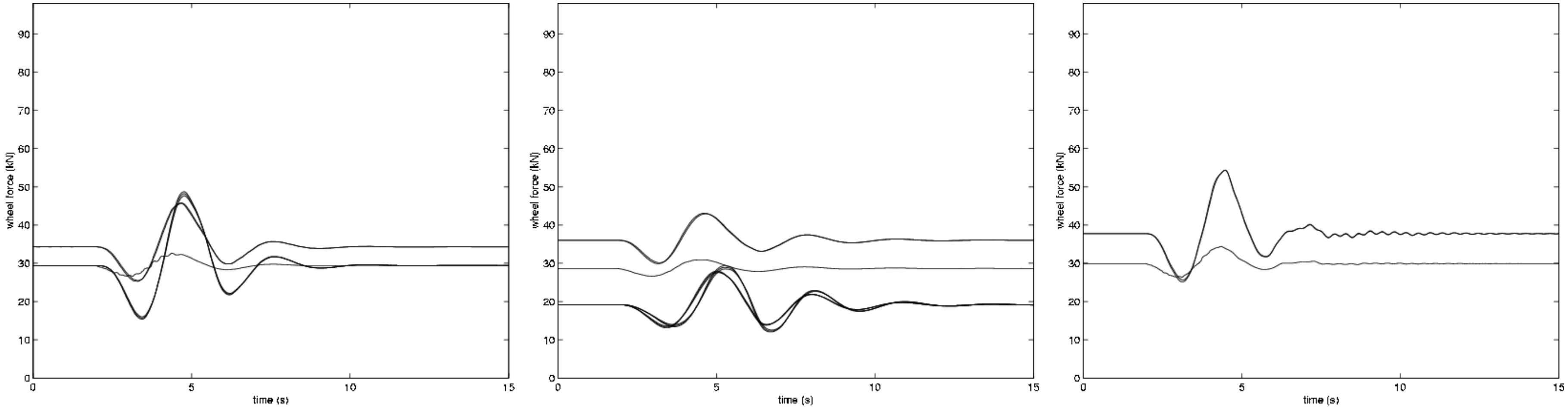


Figure A1.3: Right wheel loads during lane-change simulations for the tractor-semi-trailer, the B-train and the truck-trailer, respectively.

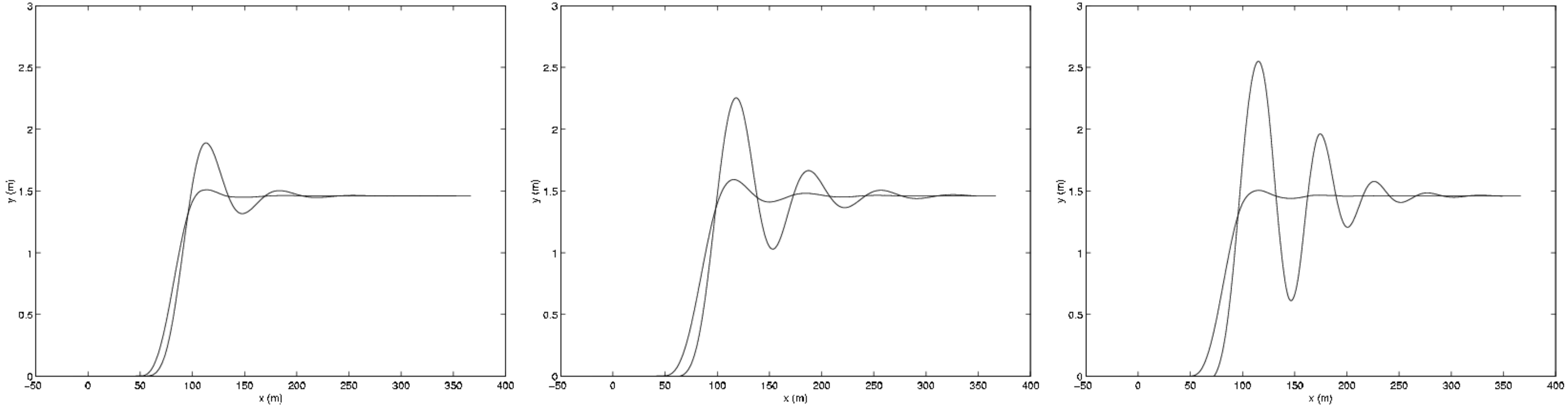


Figure A1.4: Paths for first and last axle during lane-change manoeuvres for the tractor-semi-trailer, the B-train and the truck-trailer, respectively.

Figures A1.5 to A1.7 show plots of the axle paths during a 90 degree turn at 10 kph and 13 kph. Notice that the inboard off-tracking is less at higher speeds due to increased lateral acceleration.

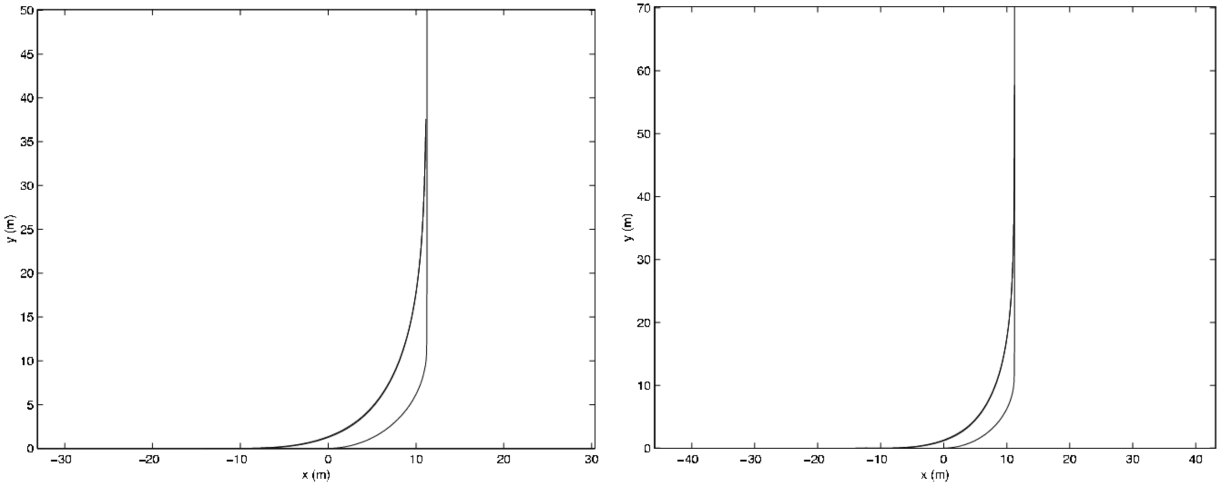
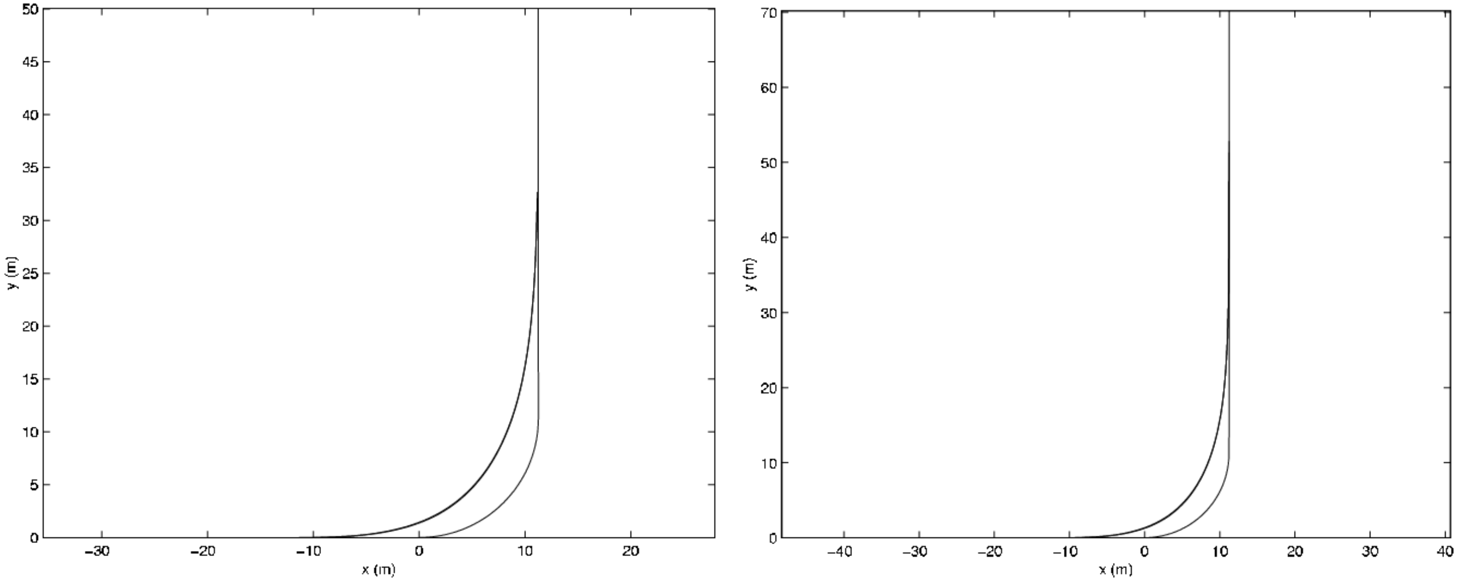


Figure A1.5: Paths of first and last axles for slow turn for the tractor-semi-trailer.



A1.6: Paths of first and last axles for slow turn for the B-train.

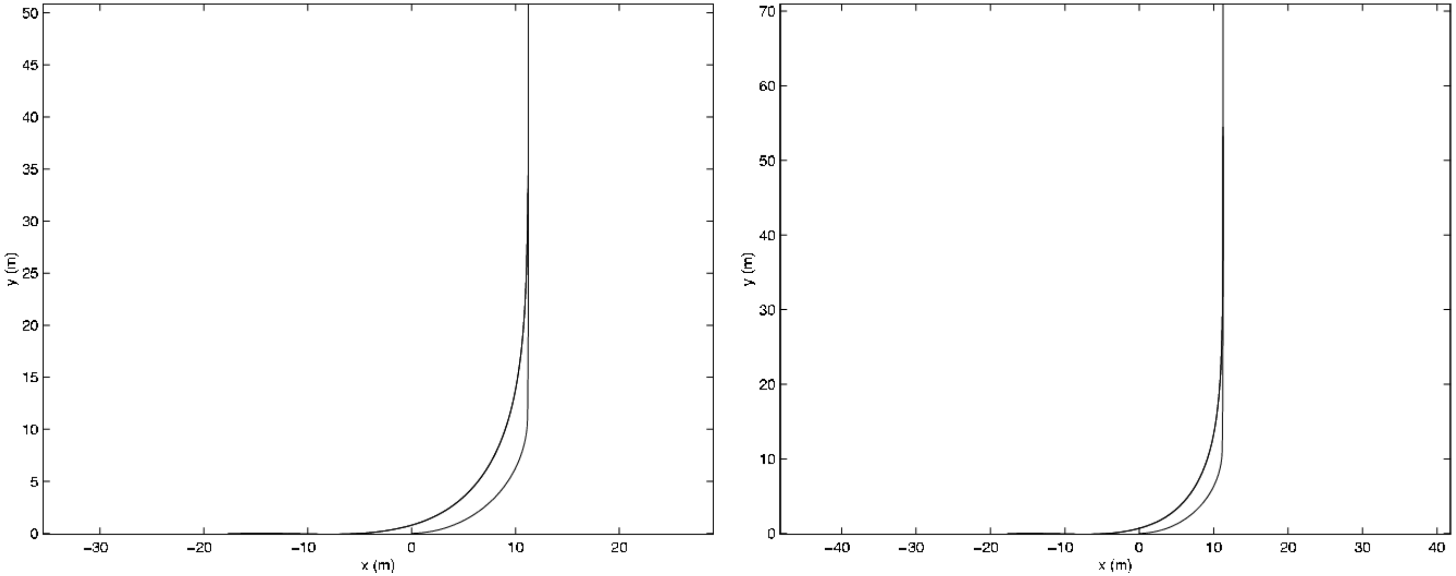


Figure A1.7: Paths of first and last axles for slow turn for the truck-trailer.

Figures A1.8 to A1.10 show plots of the high speed off-tracking for the three vehicles. Each figure shows the high speed off-tracking at 55 kph, 80 kph, 90 kph and 100 kph. Notice that the off-tracking increases with speed and therefore with lateral acceleration. The off-tracking was plotted rather than the axle paths because, for the high speed turn, the off-tracking is small relative to the path of the vehicle. This means the off-tracking is more difficult to detect for a high-speed larger-radius turns. (Woodrooffe and El-Gindy 1991)

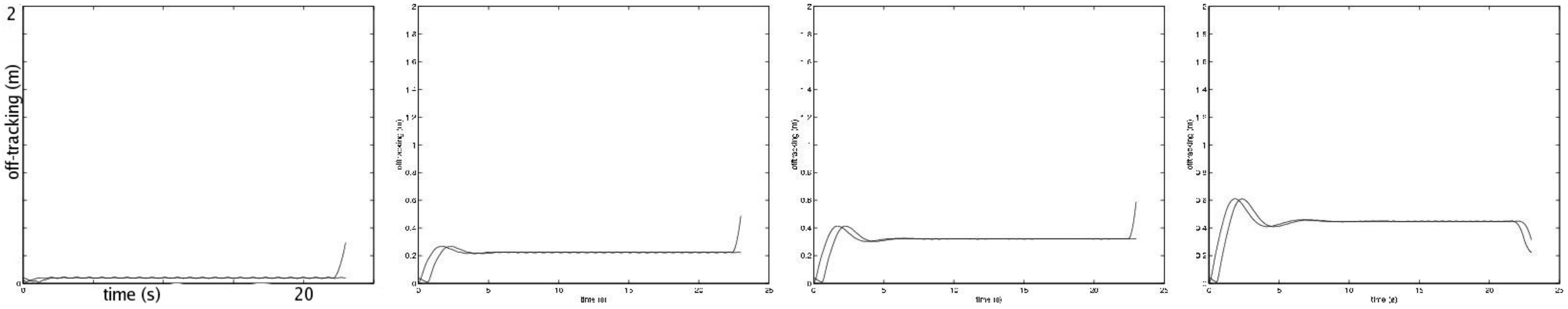


Figure A1.8: Off-tracking for high-speed turn for the tractor-semi-trailer.

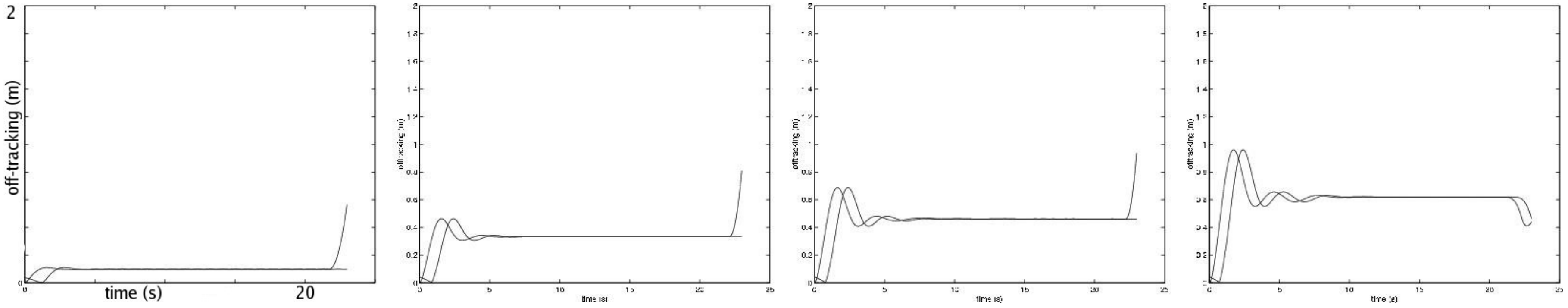


Figure A1.9: Off-tracking for high-speed turn for the B-train.

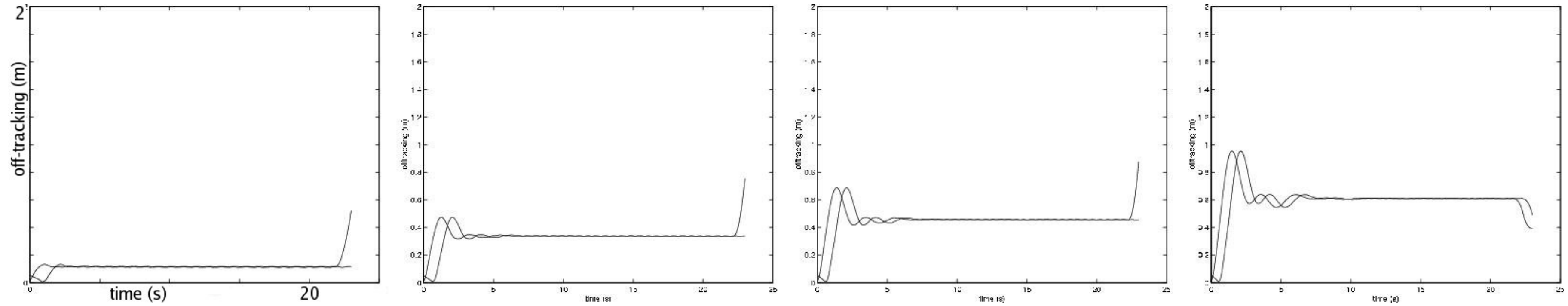


Figure A1.10: Off-tracking for high-speed turn for the truck-trailer.

The last manoeuvre was a sudden drop in the elevation of the roadway on one side of the vehicle. This manoeuvre is similar to that which might occur if the wheels on one side of the vehicle dropped off the carriageway or the shoulder of the road. Plots of axle loads for this manoeuvre have already been presented in Figure 3.3.

Appendix 2 - Manoeuvres And Performance Measures

This appendix describes the manoeuvres and performance measures that were used in this study.

Appendix 2.1 Steady-State Roll Stability

Steady-state roll stability is an expression of the magnitude of lateral acceleration required to produce vehicle rollover. It is given as a proportion of gravitational acceleration (g). Total rollover occurs when the wheels on one side of the vehicle lift off the road surface, as illustrated in Figure A2.1.

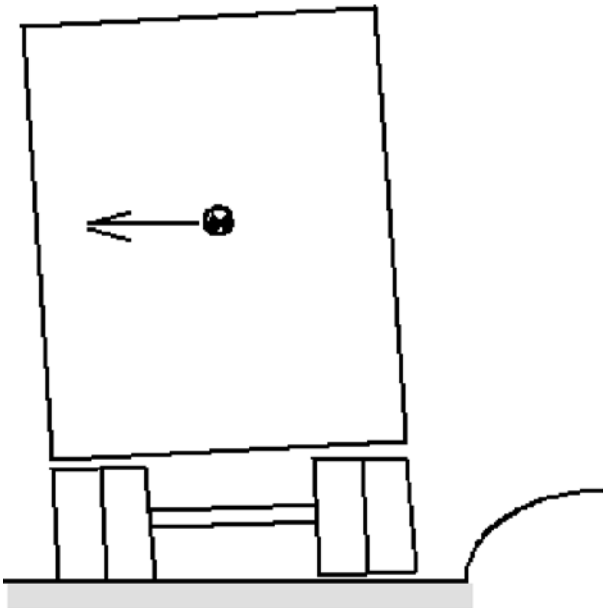


Figure A2.1: Illustration of rollover initiation.

Rollover occurs when the lateral acceleration equals or exceeds the vehicle's rollover limit (which may be assisted by roadway cross-fall or camber). Lateral acceleration on a curve is highly sensitive to speed, and the speed required to produce rollover reduces as the curve radius reduces.

Roll stability is influenced by the centre of gravity (COG) height, the effective track width provided by the axles and tyres, and the suspension roll characteristics. The COG height is affected by the chassis height, load space height, load space length and average freight density. The significance of roll stability depends on the commodity, body type and operation involved.

This performance measure is evaluated in terms of the steady-state lateral acceleration at which all wheels on the inside of the turn have lifted off the road surface. This is accomplished by increasing the steer angle of a vehicle unit until all axles on one side of a given vehicle unit lift off.

Appendix 2.2 Rearward Amplification

When articulated vehicles undergo rapid steering, the steering effect at the trailer is magnified, and this results in increased side force, or lateral acceleration, acting on the rear trailer. This in turn, increases the likelihood of the trailer rolling over under some circumstances. As an example, a truck faced with the need to change lanes quickly on a motorway to avoid an accident can do so at less risk if it has favourable rearward amplification characteristics.

Similarly, steering from side to side produces more lateral movement at the rear unit than at the hauling unit. Rearward amplification (RA) is defined as the ratio of the lateral acceleration at the centre-of-gravity (COG) of the rearmost unit to that at the hauling unit in a dynamic manoeuvre of a particular frequency. Rearward amplification expresses the tendency of the vehicle combination to develop higher lateral accelerations in the rear unit when undergoing avoidance manoeuvres; it is therefore an important consideration, additional to roll stability of the rear unit, in evaluating total dynamic stability. Rearward amplification also relates to the amount of additional road space used by the vehicle combination in an avoidance manoeuvre.

The number of articulation points and the overall length generally influences rearward amplification. Other important factors are the cornering stiffnesses of the trailer tyres and their relationship with the axle weights of the trailer. While rearward amplification is an important performance attribute for multi-articulated vehicles, it is generally of lesser significance for tractor-trailers.

This performance measure was evaluated in terms of the SAE standard scenario for measuring rearward amplification (SAE 1993). This SAE standard defines a single lane-change manoeuvre to be negotiated at a constant speed of 88 km/h (55 mph), and the test is illustrated in Figure A2.2. As the SAE standard does not include analytical procedures for the results of computer simulations, the methods developed for the RTAC Study (RTA 1986), and subsequently refined by the National Research Council of Canada (Woodrooffe and El-Gindy 1991) are adopted. Rearward amplification is determined as the ratio of peak trailer lateral acceleration to peak tractor lateral acceleration.

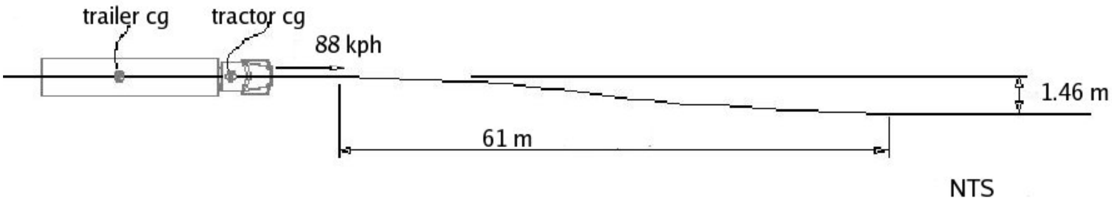


Figure A2.2: Rearward amplification of lateral acceleration.

Appendix 2.3 Load Transfer Ratio

Load transfer ratio (LTR) is defined as the proportion of load on one side of a vehicle unit transferred to the other side of the vehicle in a transient manoeuvre. Where vehicle units are roll coupled as in tractor-trailers and B-trains, the load transfer ratio is computed for all axles on the vehicle. When the load transfer ratio reaches a value of 1, rollover is about to occur. The LTR is a vital measure of rollover stability and is particularly relevant to high-speed operations in dense traffic.

This performance measure is evaluated in terms of the SAE standard scenario for measuring rearward amplification (SAE 1993). This SAE standard defines a single lane-change manoeuvre to be negotiated at a constant speed of 88 km/h (55 mph), and the test is illustrated in Figure A2.5. Note that the SAE manoeuvre actually represents a partial lane change. As the SAE standard does not include analytical procedures for the results of computer simulations, the methods developed for the RTAC Study (RTA 1986), and subsequently refined by the National Research Council (NRC) of Canada (Woodrooffe and El-Gindy 1991) were adopted. LTR was determined as the peak value of the proportion of load transferred from one side of the tractor-trailer to the other, during the standard lane-change manoeuvre.

Appendix 2.4 Low-Speed Off-tracking

Low-speed off-tracking represents a measure of the swept path of the vehicle and its lateral road space requirement when turning at intersections or when turning into loading areas.

This performance measure is evaluated for a standard 90 degree right-hand turn of radius 12.8 metres (measured at the centre of the steering axle) negotiated at a speed of 5 km/h (Woodrooffe and El-Gindy 1991). This manoeuvre is illustrated in Figure A2.3. The low-speed off-tracking is determined as the maximum radial distance between the path of the midpoint of the steer axle and the path of the midpoint of the rearmost trailer axle.

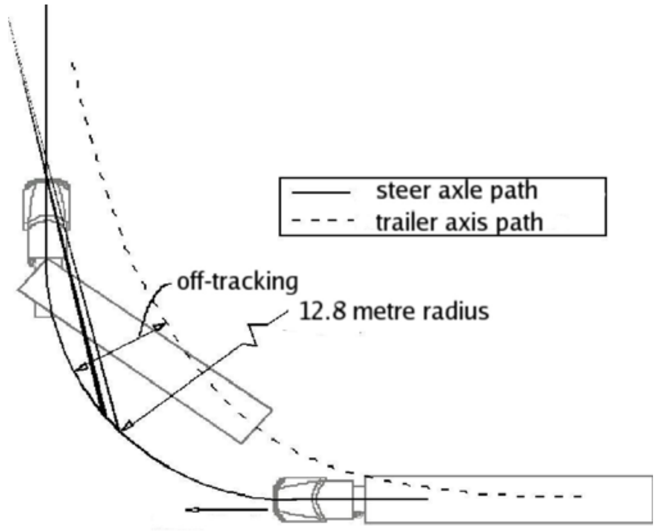


Figure A2.3: Low speed off-tracking.

In addition, the swept width of the vehicle's path is determined. This is the maximum radial distance between the outer and inner extremities of the swept path of the vehicle and may be approximated by the off-tracking plus the width of the vehicle.

Appendix 2.5 High-Speed Off-tracking

High-speed off-tracking is defined as the extent to which the rearmost tyres of the vehicle track outboard of the tyres of the hauling unit in a steady turn at highway speed. High-speed off-tracking relates closely to road width requirements for the travel of combination vehicles. This manoeuvre is illustrated in Figure A2.4.

This performance measure is evaluated for a constant-radius curve of radius 393 metres (1290 ft), with a planar surface, negotiated at a speed of 100 km/h (62 mph); this manoeuvre produces a constant lateral acceleration of 0.2 g and is used in the RTAC Study (RTA 1986). High-speed off-tracking was determined as the radial distance between the path of the centre of the steer axle and the path of the centre of the rearmost trailer axle.

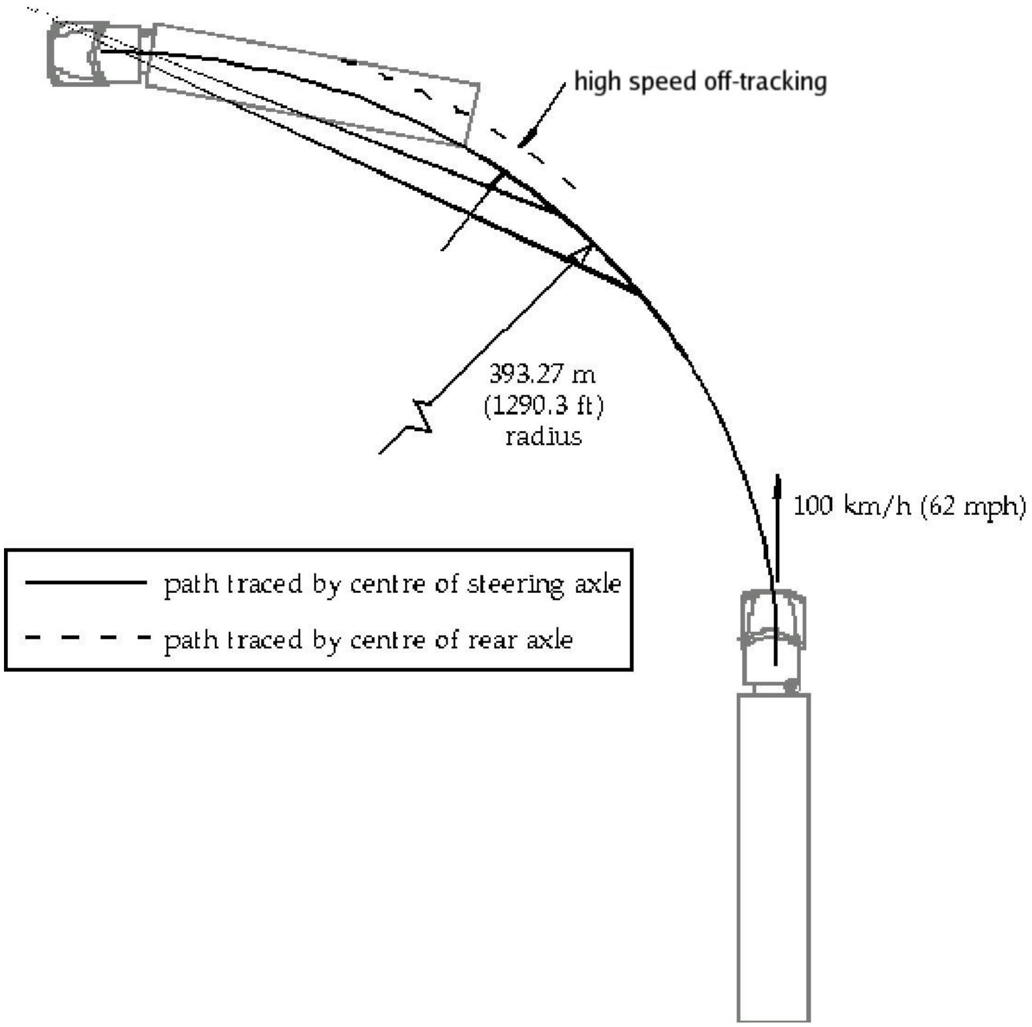


Figure A2.4: High Speed Off-tracking.

Appendix 2.6 High-Speed Transient Off-tracking

Transient high-speed off-tracking is a measure of the lateral excursion of the rear of the vehicle with reference to the path taken by the front of the vehicle during a dynamic manoeuvre as shown in Figure A2.5. This expresses the amount of additional road space used by the vehicle combination in an avoidance manoeuvre.

This performance measure is evaluated in terms of the SAE standard scenario for measuring rearward amplification and transient high-speed off-tracking (SAE 1993). This SAE standard defines a single lane-change manoeuvre to be negotiated at a constant speed of 88 km/h (55 mph). Transient high-speed off-tracking is determined as the peak lateral offset between the path of the centre steer axle and the centre of the rearmost trailer axle.

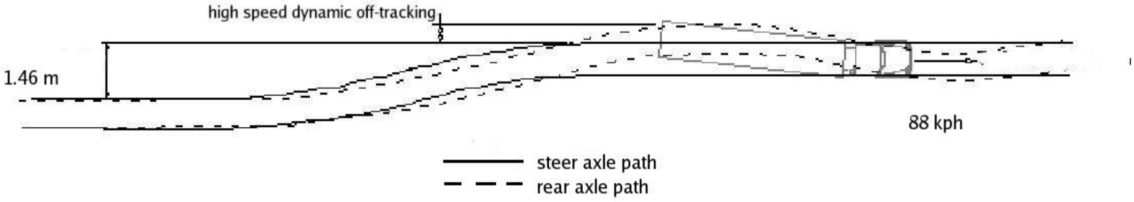


Figure A2.5: High-Speed Transient Off-tracking.