

# **A METHOD FOR QUANTIFYING THE RELATIVE RISK OF ROLLOVER OF TWO ROAD FREIGHT OPTIONS**

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## **ABSTRACT**

Two proposed heavy vehicle configurations were being considered for the transportation of dangerous goods in remote Western Australia. One of the proposed configurations offered much greater payload capacity, but had less dynamic stability. A research project was established to quantify the relative risk of rollover of the two options taking into account not only the reduced dynamic stability of the larger configuration but the reduced exposure of the larger configuration that resulted from the reduced number of required trips. The assessment was based on the risk of both steady-state rollover and dynamic rollover due to rearward amplification. For a known rear trailer rollover threshold and a known rearward amplification, the critical steer axle lateral acceleration input for dynamic rollover could be determined. A recent field operational test conducted by the University of Michigan Transportation Research Institute (UMTRI) characterized a fleet of cryogenic tankers operating in the State of Michigan in terms of the probability distribution of steer axle lateral acceleration resulting from driver input. This information was used to quantify the relative risk of the critical steer axle lateral acceleration input being exceeded. The analysis first showed that the smaller configuration posed less risk, but minor design changes to the larger configuration allowed it to be seen as the preferred option.

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## 1 INTRODUCTION

It is common practice in Australia to couple semi-trailers in series when traveling through remote areas because of the enormous increase in efficiency that is gained. One road train can haul two or three times the payload of a tractor-semi-trailer.

In most Australian states and territories, road trains are allowed to operate on defined road networks that are sufficiently distant from populated areas such as capital cities and the east coast. The extent of network access is dependent upon the type of road train, with double road trains having greater access than triple road trains. Figure 1 illustrates this point.

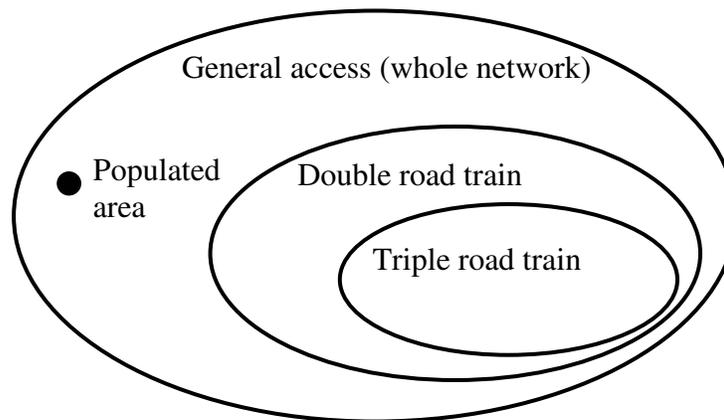


Figure 1. Road train access to the road network

With double road trains having access to all of the triple road train network, there is a potential for regulators to consider certain operations intended for the triple road train network to be suitable only for double road trains on safety grounds. This paper presents an example of such an occurrence in Western Australia and demonstrates a method used to quantify the relative rollover risk of the double road train and triple road train options in response to a request by the regulator. This method is equally applicable to smaller articulated vehicles such as tractor-semi-trailers and truck-trailers.

## 2 VEHICLE CONFIGURATION OPTIONS

The vehicle configurations being compared are a double road train ('A-double') and a triple road train ('A-triple'). Figure 2 shows the layout of each vehicle.

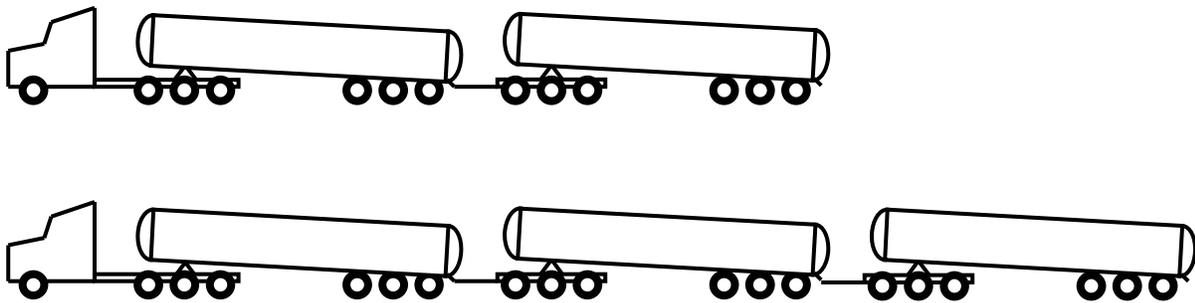


Figure 2. A-double and A-triple configurations

Being intended for the transportation of Liquefied Natural Gas (LNG), concerns were raised by the state's dangerous goods regulator that the operation may not be suitable for triple road trains because of a perception of increased rollover risk and highly undesirable outcomes in the event of a rollover. It was requested that the relative rollover risk be quantified prior to approval of one of the vehicle options.

## 3 STABILITY ASSESSMENT METHOD

The rollover risk comparison was based on a stability assessment conducted by computer simulation of vehicle dynamics using AutoSim. The assessment determined both the steady-state and dynamic rollover stability of each vehicle option.

### 3.1 Steady-state rollover

Steady-state rollover stability is quantified by the Static Rollover Threshold (SRT) of a vehicle (National Transport Commission 2005). SRT is the level of lateral acceleration that a vehicle can sustain without rolling over during a turn. The SRT is expressed as a fraction of the acceleration due to gravity in units of 'g', where 1 g is an acceleration of  $9.807 \text{ m/s}^2$  corresponding to the force exerted by the earth's gravitational field. High values of SRT imply better resistance to rollover.

To determine the SRT of a vehicle, the vehicle must be driven along a specified circular path at an initial speed that is at least 10 km/h slower than the speed at which the rollover

instability will occur. From the initial speed, the driver must increase the speed of the vehicle at a slow, steady rate until the point of rollover. Alternatively, a tilt test can be performed.

### 3.2 Dynamic rollover

Dynamic rollover stability is quantified by the Rearward Amplification (RA) of a vehicle (National Transport Commission 2005). A dynamic lane change manoeuvre is the test used to measure the RA of a vehicle combination. RA generally pertains to heavy vehicles with more than one articulation point, such as truck-trailers and road train combinations. RA describes the tendency for the trailing unit(s) to experience higher levels of lateral acceleration than the hauling unit during a dynamic manoeuvre. It is an important safety issue in rapid path-change manoeuvres as it can lead to rear-trailer rollover.

As the name suggests, each unit in the combination amplifies the lateral acceleration of the unit immediately ahead of it, and thus amplification of lateral acceleration increases toward the rear of the vehicle. Lower values of rearward amplification indicate better performance. Higher values of rearward amplification imply higher probabilities of rear-trailer rollover. RA improves with fewer articulation points, a shorter distance from the CG of the hauling unit to the hitch point, roll-coupling through turntables at articulation points, shorter coupling rear overhang, longer drawbar lengths on dollies, longer trailer wheelbase, and tyres with higher cornering-stiffness.

The intention of the lane change manoeuvre is to produce a known lateral acceleration at the steer axle, at a given frequency, and to record the lateral acceleration experienced at the rear unit. The standard lane change used in Australia (National Transport Commission 2005) uses a frequency of 0.4 Hz, with a peak lateral acceleration of 0.15 g at the steer axle—commonly reduced to 0.1 g for testing road trains—at a speed of 88 km/h. The ratio of peak lateral acceleration at the rear unit to that at the steer axle is the RA of the vehicle.

## 4 RISK ASSESSMENT METHOD

A study conducted by Winkler et. al. (2004) measured lateral acceleration input on a fleet of six tractor-semi-trailers hauling liquid nitrogen in commercial service for a period of one year. The study included 23 drivers, covering more than 700,000 km over almost 10,000 driving hours. An extremely large and potent database was created, from which valuable information on driver behaviour could be extracted. Two cumulative histograms of lateral acceleration input determined from Winkler's study are used as the basis for the present study.

### 4.1 Steady-state rollover

Steady-state rollover will occur when the steady-state lateral acceleration input to the vehicle exceeds the vehicle's SRT. To quantify the relative risk of two vehicles experiencing a steady-state rollover, one must quantify and compare the fraction of total driving time that a driver is likely to induce steady-state lateral acceleration greater than the vehicle's SRT.

The graph shown in Figure 3 presents the fraction of travel time spent above a given lateral acceleration *when driving in curves*. The graph separately displays data for four different speed ranges, because drivers in the Winkler study exhibited a tendency to induce higher levels of lateral acceleration during small radius, low-speed turns than in large radius, high-speed turns.

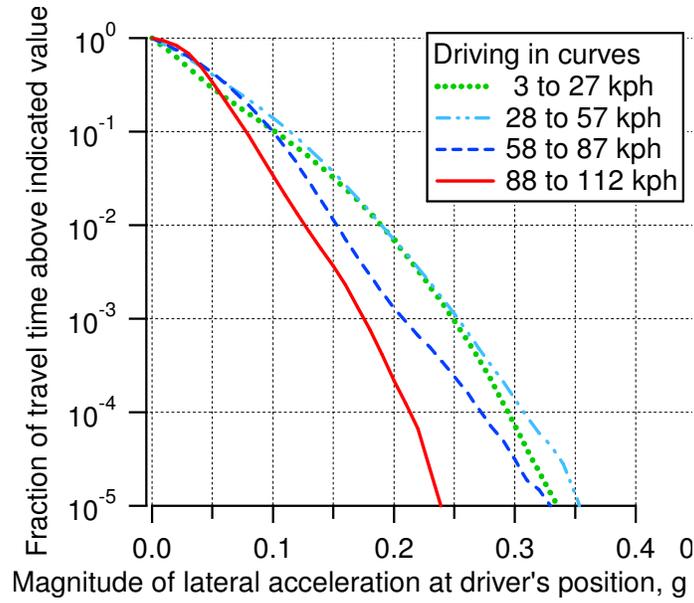


Figure 3. Histograms of lateral acceleration – driving in curves (Winkler et. al. 2004)

By comparing the fraction of travel time above one vehicle’s SRT with the fraction of travel time above another vehicle’s SRT, the relative rollover risk can be determined. For vehicles with SRT beyond the limits of the graph, an extrapolation should be performed on the basis of a polynomial curve of best fit.

A weakness in the method is that it is assumed that the driving behavior curves extracted from Winkler’s study reflect the behavior of drivers of all heavy vehicles, regardless of their stability. In reality, vehicles with different levels of stability—and different yaw/roll dynamics—would result in drivers adopting behaviors different to those depicted by Figure 3.

#### 4.2 Dynamic rollover

Dynamic rollover will occur when the lateral acceleration input to the vehicle has a frequency in the vicinity of the vehicle’s natural yaw frequency and a magnitude that exceeds the critical level defined by Equation 1.

$$LA_{CRIT} = \frac{SRT}{RA} \quad (\text{Eqn. 1})$$

In other words, a vehicle with a rear trailer SRT of 0.4 g and a RA of 2.0 will experience dynamic rollover if the lateral acceleration input exceeds 0.2 g at or near the vehicle’s natural yaw frequency, because the 0.2 g input to the steer axle will become a 0.4 g input to the rear trailer due to the rearward amplification of 2.0.

The natural yaw frequency of most combination vehicles is in the range 0.3 to 0.5 Hz. Very short duration pulses of high magnitude lateral acceleration will not cause dynamic rollover because they do not contain enough energy to sufficiently excite the dynamic system. The method described herein does not account for the frequency or duration of the lateral acceleration input; only the magnitude is considered. However, being a relative comparison between two vehicles, neglecting the frequency and duration of lateral acceleration inputs should have no

effect on the accuracy of the result provided it can safely be assumed that lateral acceleration inputs of sufficient frequency and duration for rollover comprise the same percentage of total inputs across the range of lateral acceleration magnitudes.

To quantify the relative risk of two vehicles experiencing a dynamic rollover, one must quantify and compare the fraction of total driving time that a driver is likely to induce lateral acceleration greater than the vehicle's critical level.

The graph shown in Figure 4 presents the fraction of travel time spent above a given lateral acceleration *for all driving conditions*.

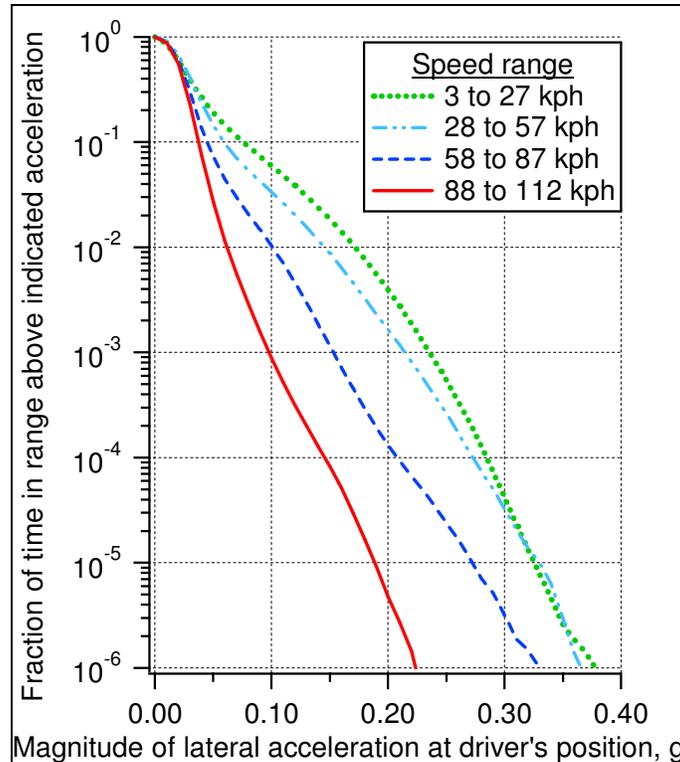


Figure 4. Histograms of lateral acceleration – all driving (Winkler et. al. 2004)

Given that the critical lateral acceleration input is typically less than the SRT, it is unlikely that extrapolation would be required for the dynamic rollover risk comparison.

## 5 ASSESSMENT RESULTS

### 5.1 Steady-state rollover

Since both vehicle configuration options were assumed to be constructed from the same trailer equipment, both vehicles demonstrated the same SRT of 0.40 g. Therefore, each vehicle was considered to be equally likely to roll over in a steady turn.

### 5.2 Dynamic rollover

RA was determined for each vehicle using dynamic lane changes having peak lateral acceleration inputs of 0.1 g, frequencies of 0.4 Hz and speeds of 60, 90 and 100 km/h, representing the speed limits imposed on the vehicles in town and highway travel (Table 1).

While the road train speed limit is 100 km/h in Western Australia, a reduced speed limit of 90 km/h was considered for the proposed triple road train option.

Table 1. RA results for each vehicle option

<i>Speed (km/h)</i>	<i>Rearward Amplification (RA)</i>	
	<i>A-double</i>	<i>A-triple</i>
60	0.87	1.00
90	1.98	3.21
100	2.33	3.84

Using the results of Table 1 in conjunction with the previously determined SRT values, the critical lateral acceleration inputs for dynamic rollover are presented in Table 2 using Equation 1.

Table 2. Critical lateral acceleration input for each vehicle option

<i>Speed (km/h)</i>	<i>Critical lateral acceleration input (g)</i>	
	<i>A-double</i>	<i>A-triple</i>
60	0.46	0.40
90	0.20	0.12
100	0.17	0.10

Using the relationships presented in Figure 4, the relative rollover risk of the A-triple—expressed as the number of times more likely it is to roll over than the A-double—is presented in Table 3 and Table 4. These tables take into account the factor of 1.5 arising from the increased efficiency of the A-triple affording fewer trips and hence reduced exposure, which directly impacts on rollover risk. The tables show, for example, that the A-triple traveling at 90 km/h is 6.4 times more likely to roll over than the A-double traveling at 100 km/h. In all cases, the A-triple is more likely to roll over than the A-double.

Table 3. Relative dynamic rollover risk of A-triple compared with A-double (highway speed)

	<i>A-triple at 90 km/h</i>	<i>A-triple at 100 km/h</i>
<i>A-double at 90 km/h</i>	42.1	118.3
<i>A-double at 100 km/h</i>	6.4	18.1

Table 4. Relative dynamic rollover risk of A-triple compared with A-double (town speed)

	<i>A-triple at 60 km/h</i>
<i>A-double at 60 km/h</i>	7.3

## 6 REVISING THE A-TRIPLE DESIGN FOR BETTER PERFORMANCE

The A-triple design was revised to bring about a better comparison of rollover risk of the two vehicle options. The most effective modification was the specification of a trailer suspension with greater roll-stiffness to increase SRT and reduce RA. Other modifications were

made to the vehicle dimensions, although these were mostly restricted by regulations and physical or commercial limitations.

### 6.1 Steady-state rollover

With the revised design the A-triple demonstrated a SRT of 0.43 g, compared with the original 0.40 g. The relationships presented in Figure 3 can now be used to quantify the relative risk of steady-state rollover (Table 5). It can be seen that the small improvement in SRT dramatically improves the rollover risk to about one tenth, or less, of that of the A-double across all speed ranges.

Table 5. Relative risk of steady-state rollover

<i>Speed range (km/h)</i>	<i>Relative risk of rollover (revised A-triple compared with A-double)</i>
3 to 27 km/h	0.10
28 to 57 km/h	0.11
58 to 87 km/h	0.08
88 to 112 km/h	0.01

### 6.2 Dynamic rollover

Considering the difference in dynamic rollover risk observed in the previous analysis, it was considered necessary to impose a speed limit of 90 km/h on the proposed A-triple in addition to the design changes. A speed limit less than 90 km/h would render the operation economically infeasible. The relative risk of dynamic rollover at highway speed is therefore compared on the basis of the A-triple at 90 km/h versus the A-double at the accepted speed limit of 100 km/h. The RA of the revised A-triple at 90 km/h is 2.78 (down from 3.21) and at 60 km/h it is 0.71 (down from 1.00). The relative rollover risks are presented in Table 6.

Table 6. Relative risk of dynamic rollover

	<i>Revised A-triple at 60 km/h</i>	<i>Revised A-triple at 90 km/h</i>
<i>A-double at 60 km/h</i>	< 0.001	n/a
<i>A-double at 100 km/h</i>	n/a	1.6

It can be seen that the revised A-triple offers far superior dynamic rollover risk at town speeds and comparable rollover risk—about 1.6 times more—at highway speeds, compared with the A-double.

## 7 CONCLUSION

The revised A-triple design was found to have very much less risk of steady-state rollover and slightly more risk of dynamic rollover than the original A-double design. To determine the net relative risk, the likely circumstances and consequences of steady-state and dynamic rollover were considered.

Steady-state rollover is most likely to occur when cornering at low to moderate speeds because it requires a high lateral acceleration input, which drivers are more likely to induce at low to moderate speeds. Dynamic rollover is most likely to occur at high speeds, where the RA of a vehicle is at its greatest and the critical lateral acceleration input is at its lowest.

Cornering at low to moderate speeds is most likely to occur in a somewhat populated area, while traveling at high speeds is most likely to occur on the open road (in this case, a remote highway).

The consequences of rollover in a populated area are much worse than those of a rollover in a remote area, so it is considered that much more weight should be placed on the relative risk of steady-state rollover. Overall, it is considered that the revised A-triple design poses less risk of rollover than the original A-double design.

## **8 REFERENCES**

National Transport Commission 2005, Rules for assessment of potential performance-based standards vehicles, National Transport Commission, Melbourne.

Winkler, C, Sullivan, J, Bogard, S & Hagan, M 2004, 'Observations on the lateral performance of truck drivers', *International symposium on heavy vehicle weights and dimensions, 8<sup>th</sup>, 2004, Muldersdrift, South Africa*, Documentation Transformation Technologies, Johannesburg, 11pp.