BEHAVIOUR OF ARTICULATED VEHICLES ON CURVES

Rod George

ARRB

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BEHAVIOUR OF ARTICULATED VEHICLES ON CURVES.

by

R.M. GEORGE

AUSTRALIAN ROAD RESEARCH BOARD

SUMMARY:

Heavy vehicle crashes usually result in truck damage, loss or damage of load, damage to the property of other parties and present a risk to other road users.

In Australia between the years 1982 and 1989, 858 (13%), of the reported articulated vehicle crashes were roll-overs.

ARRB has undertaken a study to assess the feasibility of providing the driver of an articulated vehicle with information on the roll-stability of the trailer unit. The study involved the investigation of the actual roll-behavioural characteristics of articulated vehicles as they approach the roll-threshold.

Vehicle safety researchers throughout the world have carried out theoretical studies and produced computer models which have concluded that a number of factors influence articulated vehicle roll stability. These include load centre of gravity (COG) height, suspension roll stiffness, prime-mover/trailer suspension matching, and track width.

To gather information on these factors an in-service behavioural study was carried out using a sample of typical Australian articulated vehicles during their normal operation.

Five articulated vehicles were instrumented to measure the following: the lateral acceleration at the trailer rear and in the prime-mover cabin along with the yaw rate, the vertical load shift on both sides at the mid-point of the trailer suspension, distance and the elapsed time for each data sample from the depot. The instantaneous vehicle speed was calculated from the last two parameters - distance and time. The effective radius of curve of the prime-mover travel was estimated from the yaw rate and the vehicle speed. The superelevation of the road surface (cross-slope), was estimated using the lateral acceleration in the cabin, yaw rate and the vehicle speed.

The ARRB tilt deck was used to determine the roll-threshold level for each of the five test vehicles in the laden condition. Information from the tilt testing allowed the following to be determined: the effective load COG height, the roll-factor of the prime-mover cabin (i.e. the ratio of the tilt deck angle to the roll angle in the cabin), and calibration of the vertical load sensing transducers mounted on the trailer.

The paper describes the test methodology, the test vehicles, their roll-characteristics and summarises the findings to date.

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Heavy vehicle crashes usually result in truck damage, loss or damage of load, damage to the property of other parties and present a risk to other road users.

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Five articulated vehicles were instrumented to measure: the lateral acceleration at the trailer rear and in the prime-mover cabin along with the yaw rate, the lateral load shift on both sides at the mid-point of the trailer suspension, distance and the elapsed time for each data sample from the depot. The instantaneous vehicle speed, the effective radius of curvature of the prime-mover travel and the superelevation of the road surface (cross-slope) were also estimated.

The ARRB tilt deck was used to determine the roll-threshold level for each of the five test vehicles in the laden condition. Information from the tilt testing allowed the following to be determined: the effective load centre of gravity (COG) height, the roll-factor of the prime-mover cabin (i.e. the ratio of the tilt deck angle to the roll angle in the cabin), and calibration of the vertical load sensing transducers mounted on the trailer.

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ACKNOWLEDGEMENTS:

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IPEC Road Express
Linfox Group
Public Transport Corporation Victoria
Shell Co. of Australia Limited

CONTENTS

1. INTRODUCTION

When an articulated vehicle crashes the probability of the loss of load and damage to other parties' property is high. Although the history of roll-overs of articulated vehicles is not significantly high considering the number of vehicles and kilometres travelled, a reduction in accidents would represent a large savings in lives, damage and inconvenience.

Due to the isolation of the cabin, most drivers of articulated vehicles do not receive feedback of an imminent roll-over. A study investigating the feasibility of providing drivers of articulated vehicles with information on the roll-stability of their trailer is being conducted at the Australian Road Research Board. In order to develop such a device it is necessary to have an understanding of the behaviour of articulated vehicles on or about the onset of roll-over.

A program was undertaken to gather in-service roll-behavioural information on a number of Australian articulated vehicles.

2. BACKGROUND

In Australia over the eight years, 1982 - 1989 articulated vehicles were involved in a total of 6,599 fatal and hospital admission crashes, Hayworth et al (1991). Roll-overs accounted for 858 (13%) of these crashes. Of the 858 roll-over crashes, 118 (14%) result in fatalities and 740 (86%) caused injury resulting in hospitalisation.

Of the 6,599 fatal and hospital admission crashes, 31% occurred on a curve. Approximately one third, of the total articulated vehicle crashes occur within city limits, and over half occur on roads with a speed limit equal to or greater that 100 km/h.

In addition to these accidents, which were all reported, an unknown number are not reported.

Over the last three decades there has been an increasing number of theoretical and experimental studies on the roll stability of articulated vehicles, including Ervin (1986), Mai and Sweatman (1984), Miller and Barter (1973) and Nalecz and Genin (1984). Most of the studies have concluded that the Centre of Gravity (COG) height of the trailer load and the roll dynamics - suspension properties have a first order effect on the roll stability.

Mai and Sweatman (1984) in their articulated vehicle roll stability study, concluded that the COG load height of the trailer and tyre track width are primary factors affecting the roll-over threshold, and means of reducing COG should be exploited. This is because the wheel lift lateral acceleration increases by almost 0.03 g for every 100 mm reduction in effective COG height. They commented on combination behaviour stating that:

> *"There is little difference between the lateral acceleration threshold at the first wheel lift and the total roll-over. It is reasonable to consider the first wheel lift as the stability threshold of the combination."*

3. IN-SERVICE DATA COLLECTION

An in-service testing program was undertaken to provide information on roll-threshold limits and the characteristics of a sample of Australian articulated vehicles as they negotiate curves.

The objective of this program was to determine the roll-threshold for the laden vehicle, then measure and record a number of key parameters during normal urban and rural operations.

By acquiring information on a range of articulated vehicles' roll-stability thresholds, and their roll-behaviour for a range of in-service conditions, an understanding of the interactions between the suspension types, COG heights, road geometry, lateral accelerations and their associated times can be obtained.

3.1 EXPERIMENTAL VARIABLES

The proximity to roll-over of any articulated vehicle combination is determined by the following three components:

1. **The vehicle characteristics** - roll compliances as determined by the track widths, suspension types and matching, the trailer COG height, gross vehicle mass (GVM) and vehicle speed.

   These variables have been documented and discussed in previous research work, and their measurement and influence on roll-stability will be discussed in the following sections.

2. **The road geometry** - superelevation (cross-slope) and horizontal alignment (curvature).

   With the measurement of the variables: i) vehicle speed, ii) vehicle lateral acceleration, and iii) vehicle yaw rate, it is possible to estimate the above two parameters. The formulae for calculating these road geometry parameters are given in Appendix C.

3. **The driver** - inputs to control the vehicle system with the vehicle speed and steer path, which determine the level of lateral acceleration that the vehicle is subjected to.

   In determining the experimental design it was initially considered appropriate to classify the drivers into driving style groups. Whilst this information would have added another dimension, it was beyond the scope of this study.

The variables that have been identified to have influence on the roll stability of an articulated vehicle can be classified into two groups: i) those of a static nature - pertaining to each vehicle, e.g. track width, suspension type and matching, load COG height, and ii) those dynamic - varying for each incident, e.g. lateral acceleration, vehicle speed, road geometry and drivers input.

3.1.1 Vehicle Parameters

The following parameters were measured or estimated for each test vehicle:

1. The trailer COG height - this was estimated for each laden vehicle using the tilt deck facility. The procedure for estimating COG height is described in Appendix A.

2. Track Widths - this variable was measured, centre to centre of the tyre contact area for single tyres, and for dual tyres the effective centre to centre width.

3. Suspension Types - the suspension types fitted to both the prime-mover and the trailer were recorded.

4. Vehicle dimensions - the prime-mover and trailer wheel-bases and axle spacing, the trailer chassis height front and rear, the trailer load height front and rear and the fifth wheel height. The prime-mover and trailer identifications, fleet numbers, and registration numbers, were also recorded.

5. Axle masses - for each laden test vehicle the axle masses were measured and recorded.

3.1.2 Handling Variables

The following key parameters were measured and recorded for each test vehicle, during the in-service data collection phase of the program:

1. The lateral acceleration in the cabin of the prime-mover.

2. The yaw rate in the cabin of the prime-mover.

3. The lateral acceleration at chassis level on the rear of the trailer.

As the ultimate aim of the study was to provide in-service feedback information to the driver, it was decided to assess a method of acquiring the prime information for the feedback device during the behavioural data collection phase of the study. Two strain link transducers, that were primarily designed for vehicle on-board scales, were used to measure the lateral load shift. They were mounted on the chassis rails at the mid-point of trailer suspension on both the passengers and drivers sides.

3.2 TEST PROGRAM

With the active co-operation of four transport companies (Shell Company of Australia, The Public Transport Corporation Victoria (V/Line), IPEC and the Linfox Group) five test vehicles were fitted with the measuring instruments, calibrated on the ARRB tilt deck and returned to their depots for a normal trip.

An experimenter travelled with the vehicles to operate the data logging equipment. Geographical and distance comments were recorded with the data. These were used later for locating and identifying comments during data analysis.

3.3 INSTRUMENTATION

The heart of the instrumentation was the ARRB designed data logging system TruckDas. The basic operation of the TruckDas is an event triggered, distance based sampling data logger with 5 pre-trigger events recorded at the start of each logging segment. The trigger for this series of experiments was the lateral acceleration at the prime-mover, set to around $^1/_2$ of the roll-threshold acceleration value. After a trigger event occurs, the data is recorded for a pre-set time of either 20 or 30 seconds. At the conclusion of the logging session the recorded information is transferred to a portable IBM type computer and stored on a 3 $^1/_2$" disk.

The 5 variables that were logged on the TruckDas were conditioned, scaled and low-pass filtered prior to logging.

3.4 TEST VEHICLE CALIBRATION

Each test vehicle was instrumented and tested for its roll characteristics on the ARRB tilt deck.

In order to obtain realistic roll-characteristics for each test vehicle they were tilt tested in laden condition. The oil tanker vehicles were loaded with water 'as close as possible' to the operating axle loads. All other vehicles were tilt tested laden with the actual or similar load carried during the in-service data acquisition trips.

The tilt test provided three sets of information:

3.4.1 Wheel Lift Points

The trailer, drive and steer axle groups lateral load transfer values were recorded as a function of the tilt deck angle.

For safety reasons the test vehicles were not taken to the full wheel-lift limit. To estimate this limit the data obtained from the tilt deck was extrapolated to the 100% load transfer point. The value of lateral acceleration required to produce the 100% load transfer at the trailer is defined as the ***roll-threshold.***

The tilt deck angle was converted to the fraction of the gravitational force required to produce the wheel lift:

$$a = \tan(\alpha) \qquad (1)$$

where α tilt deck angle (radians)

and a equivalent lateral acceleration (g)

The tilt deck angle, shown as equivalent gravitational force, the projected wheel-lift point and tilt test axle loads are shown for all test vehicles in Appendix B.

3.4.2 Cabin Roll factor calibration

This characteristic is required for the estimation of the cross-slope, and is the ratio of the tilt deck angle to the tilt angle in the driver's cabin. The formula for the cross-slope calculation is given in Appendix C.

3.5 TEST VEHICLES AND ROUTES

The test routes were operation specific and where possible normal routes were travelled. However, in order not to reduce the number of curves where data may be generated, the fleet schedulers were requested to limit the use of freeways. Table I summarises the test vehicle characteristics and dimensional details are given in Appendix D:

TABLE I

TEST VEHICLE CHARACTERISTICS

Owner	Suspension Type Prime-mover	Suspension Type Trailer	Effective COG Height	Trailer Track Width	Lateral Accn. to produce wheel lift (Trailer)	Lateral Accn. to produce wheel lift (Drive)	Gross Vehicle Mass (GVM)
			(m)	(m)	(g)	(g)	(t)
Shell Oil Tanker	Mack - RST Camel Back	Freighter Six Spring	2.22	2.03	0.37	0.50	42.5
V/Line Freight	Volvo - F12 2 leaf 'B-Ride'	Teco Six Spring	3.63	1.84	0.30	0.37	36.6
IPEC Freight	Kenworth - T600 Six Rod	BPW Dual-Airbag	1.55	1.84	0.44	0.52	32.0
Linfox/Caltex Oil Tanker	Scania - P112 M 6 × 2 Hendrickson 4 Spring	Reyco	2.36	2.02	0.39	0.48	41.0
Linfox/Bunge Flour Tanker	Mercedes Benz - 2235 Six Rod	Freighter Six Spring	2.10	2.08	0.45	0.58	42.0

3.5.1 Shell Tanker

A Shell tanker was instrumented and tested on rural roads, Melbourne - Mansfield return, 360 km round trip and urban roads, Newport to Dandenong return, 100 km round trip.

3.5.2 V/Line General Freight Vehicle

The route for this test vehicle was primarily rural, Melbourne - Portland return, 720 km round trip. Data was only analysed for the return trip as the first load did not represent a typical load COG height. However, for the return trip the trailer was laden with 120 bales of wool. This produced the highest COG load height of 3.5 m.

3.5.3 IPEC Road Express

This vehicle was a cubic freight jumbo pantechnicon. The route for this testing was Melbourne to Sydney return on the Hume freeway, a 1670 km round trip. The vehicle was laden both ways.

3.5.4 Linfox/Caltex Tanker

This was similar to the Shell vehicle except for a 6 X 2 prime-mover configuration. The route was also similar to that of the Shell tanker, rural Melbourne - Alexandra 260 km round trip, and urban travel, Spotswood - Seaford, 80 km.

3.5.5 Linfox/Bunge Flour Tanker

This vehicle was carrying bulk flour and the test route was mainly rural, ARRB - Altona - Ballarat - Corowa - Albury return to Altona, some 750 km of travel.

4. DATA ANALYSIS

From each segment of logged data the following information was extracted: i) the time from zero or steady state for the trailer to reach the peak lateral acceleration level, ii) the trailer and prime-mover peak lateral acceleration levels, iii) the mean effective steer path, iv) effective cross-slope of the road surface, v) the mean vehicle speed, and vi) the distance and time from the depot.

Figure 1 shows a typical urban lateral acceleration time history, for a right/left manoeuvre. The maximum positive acceleration level at the rear of the trailer, 0.289 g, occurred 3.07 second from zero and the maximum negative acceleration, -0.275 g, 2.64 seconds from the zero crossing.

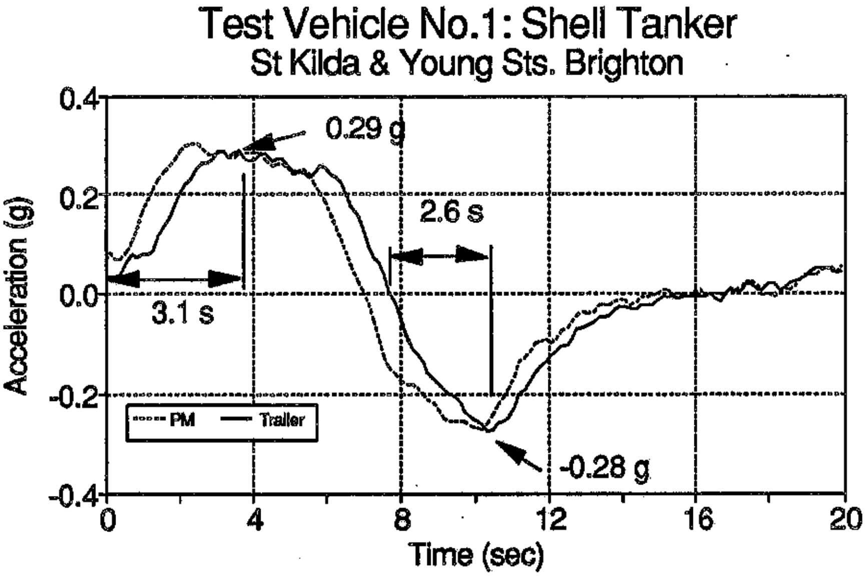

Fig. 1 - Typical urban acceleration levels and times.

Similarly Figure 2 shows a typical rural lateral acceleration time history for a right/left manoeuvre. The maximum positive acceleration level at the rear of the trailer, 0.19 g, occurred 3.87 seconds from zero and the maximum negative acceleration, -0.261 g, 4.03 seconds from the zero crossing.

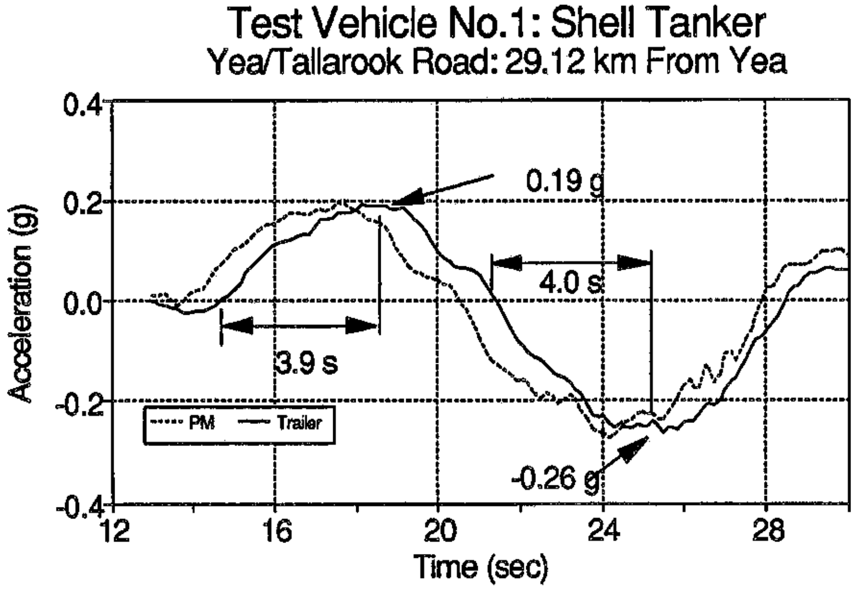

Fig. 2 - Typical rural acceleration levels and times.

For each test vehicle the maximum trailer lateral acceleration was normalised by its trailer roll-threshold value as determined by the tilt test.

5. RESULTS

5.1 Roll-threshold Limits

Figure 3 shows the distribution for the recorded lateral acceleration levels at the trailer rear, normalised by each vehicles' trailer roll-threshold. This illustrates how close to the roll-threshold the test vehicles operated. In general, these vehicles most commonly operated at a level just over half, 52% of their roll-threshold, with one instance at 92% of the roll-threshold limit.

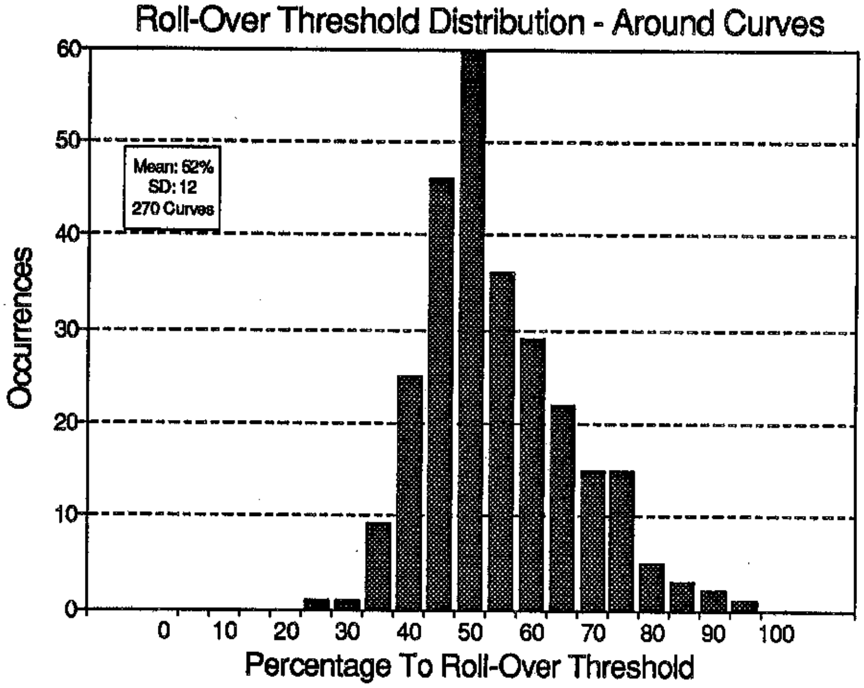

Fig. 3 - Test vehicles distribution to the roll-limit

5.2 Negotiating a Curve

The data plotted in Figure 4 illustrates the relationship between vehicle speed and the radius of curvature. The trend line is of the form:

$$\text{speed} \propto \sqrt{\text{radius}} \qquad (2)$$

This relationship is consistent with the theoretical expression - given a constant lateral acceleration;

$$a = \frac{v^2}{r} \qquad (3)$$

where v vehicle speed (m/s)

r radius of curvature (m)

and a lateral acceleration (m/s^2)

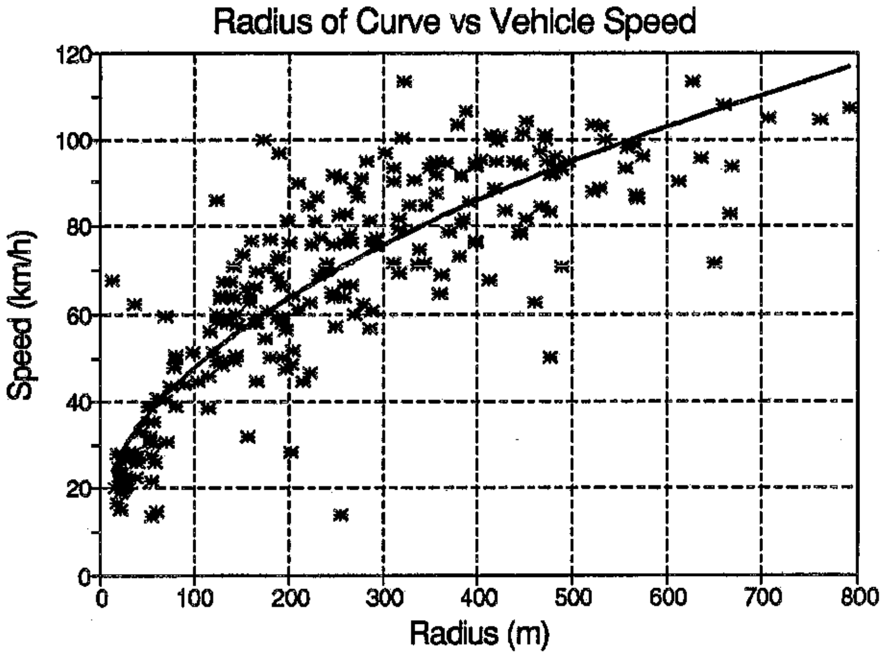

Fig. 4 - Test vehicle speed as a function of radius of curve

5.3 Time Window

One of the prime objectives of this study was to determine the feasibility of providing drivers with feedback information on the roll-stability of their trailers. Figure 5 is a plot of each measured event around a curve showing the time to reach each maximum lateral acceleration against the level from the roll-threshold.

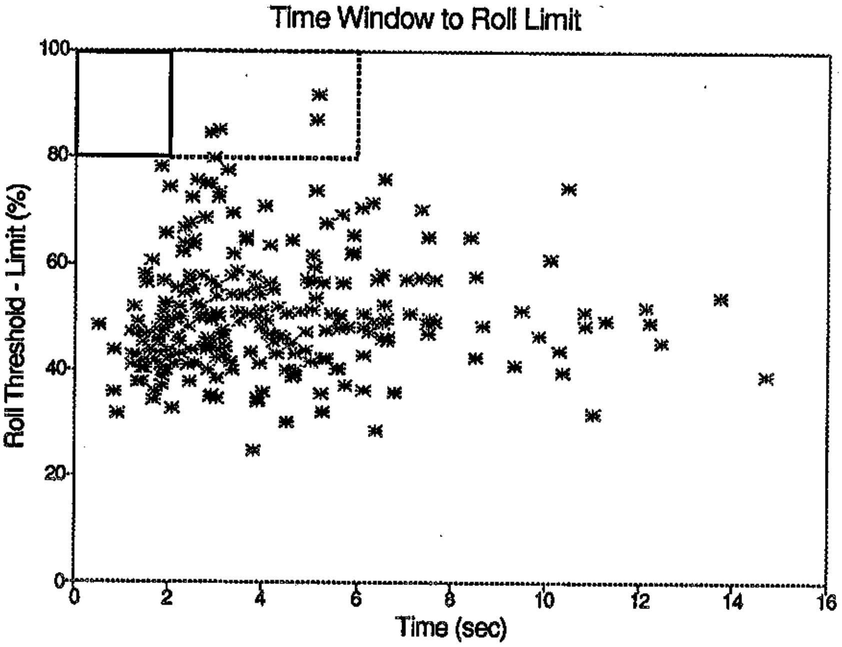

Fig. 5 - Critical recorded times to reach maximum lateral acceleration.

The solid boxed portion on the top left corner, Figure 5, is the 'critical time window', as events that take place in this region are high on the roll-limit, within 20% of potential roll-over and occur in a short time period, less than 2 seconds. The time window for the dashed box, '80% roll-threshold' is also important, as the vehicle is approaching the roll-limit, but there is more time for the driver to act. For the information obtained from these five test vehicles travelling around curves, only five events out of 269 occurred within the 80% roll-threshold.

This may seem a relatively infrequent occurrence. However, it is equivalent to an 'average' articulated vehicle coming within 20% of its roll-limit once every 715 km of travel. In Australia during 1988 the average distance travelled per articulated vehicle was 78,700 km (ABS 1988) therefore it may be concluded that, each articulated vehicle approaches its roll-limit approximately once every 3 days of travel.

6. DISCUSSION

6.1 Driver Warning Time

From the recorded information it appears that there is sufficient time to advise the driver when the trailer is within 20% of its roll-threshold.

6.2 Driver Reaction Times

The reaction time of drivers to external stimuli was studied by Triggs and Harris (1982). They observed the response times of passing motorists to a selection of conditions, *Table II*. Not all the set-up conditions presented the same urgency to the drivers. They measured reaction times for different situations, and this data suggests that response times for drivers under normal states of alertness should be taken to be not less than 1.5 seconds.

TABLE II

85th Percentile Reaction Time Values

	(sec)
"Roadworks Ahead" Sign	3.0
Protruding vehicle with tyre change	1.5
Lit vehicle under repair at night	1.5
Parked Police car	2.8
Amphometer: Beaconsfield	3.4
Amphometer: Dandenong North	3.6
Amphometer: Gisborne	3.6
Amphometer: Tynong	2.5
Railway crossing: Night (General Population)	1.5
Railway crossing: Night (Rally Drivers)	1.5
Railway crossing: Day	2.5
Car following	1.3

From: Triggs and Harris, 1982.

7. CONCLUSIONS

The results from this study show that:

1. Drivers tend to adjust the vehicle speed and steer path, to negotiate curves with a high safety margin.

2 However, once in every 3 days (on average), an articulated vehicle approaches the roll-over limit.

3 In all of the cases studied, there is sufficient time to provide the driver with feedback information to alert them that the trailer is approaching the roll-over limit.

A prototype warning device is under development, and upon its completion, further investigations are planned to validate its operation and determine its effect on driver behaviour.

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9. ABBREVIATIONS

a	Lateral acceleration (g)
COG	Load Centre of Gravity height (m)
ΔL	the change in vertical load due to the tilt angle (t)
e	Superelevation (%)
g	acceleration due to gravity (m/s^2)
H	Effective COG load height (m)
L_d	vertical load acting on the trailer axle group at the drivers side (t)
L_p	vertical load acting on the trailer axle group at the passengers side (t)
Mg	the total mass acting at the COG on the trailer group (kN)
α	the tilt angle (radians)
r	radius of curvature (m)
Rf	Roll factor (ratio) - Obtained during tilt testing, and is the ratio of the tilt deck angle to the roll angle in the prime-mover cabin.
Tw	the effective track width of the vehicle (m)
ω	prime-mover yaw rate (radians/sec)

APPENDIX A

Procedure for Estimating Trailer Centre of Gravity Load Height

The Centre of Gravity height, (H) of a laden trailer can be estimated using data acquired from a tilt table test. Using small angles of inclination, (α) less than 6 degrees, and assuming that the vehicle acts as a rigid body, i.e. the suspension does not influence the roll angle of the sprung mass, the Centre of Gravity height is estimated using geometry.

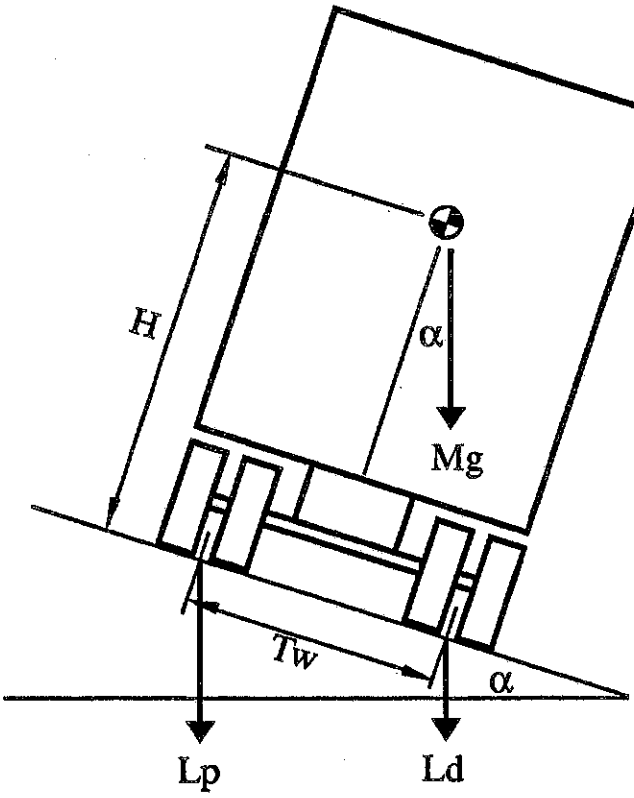


Fig. - A1 Simplified vehicle model for estimating effective COG height

Taking moments about the contact point on the low side (L_d):

$$(Mg / 2 - \Delta L) \times \alpha \times Tw = Mg\,[\alpha\,(Tw / 2 - \alpha H)] \qquad \text{(A1)}$$

where Mg total mass acting on the trailer group (t)

ΔL change in vertical load due to the tilt angle α (t)

α tilt angle (radians)

H effective COG height (m)

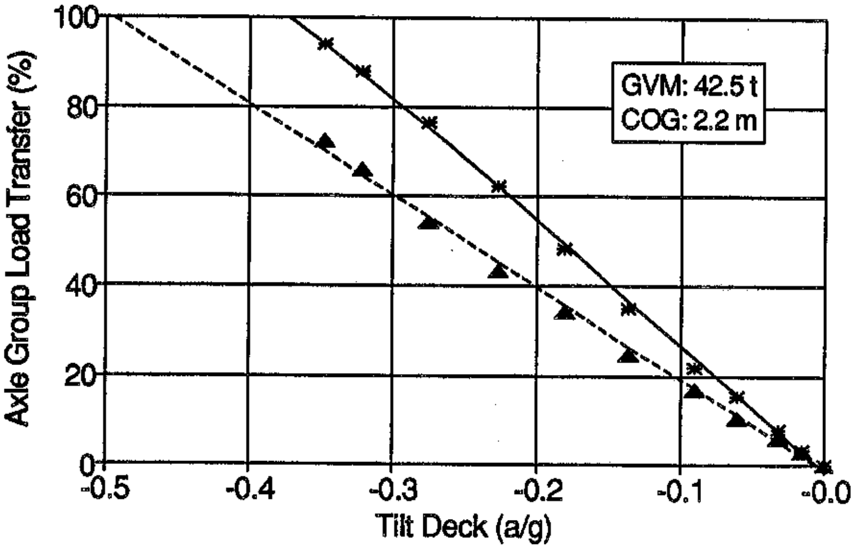
and Tw effective track width of the vehicle (m)

this reduces and simplifies to:

$$H = (\Delta L \times Tw) / Mg \times \alpha \qquad \text{(A2)}$$

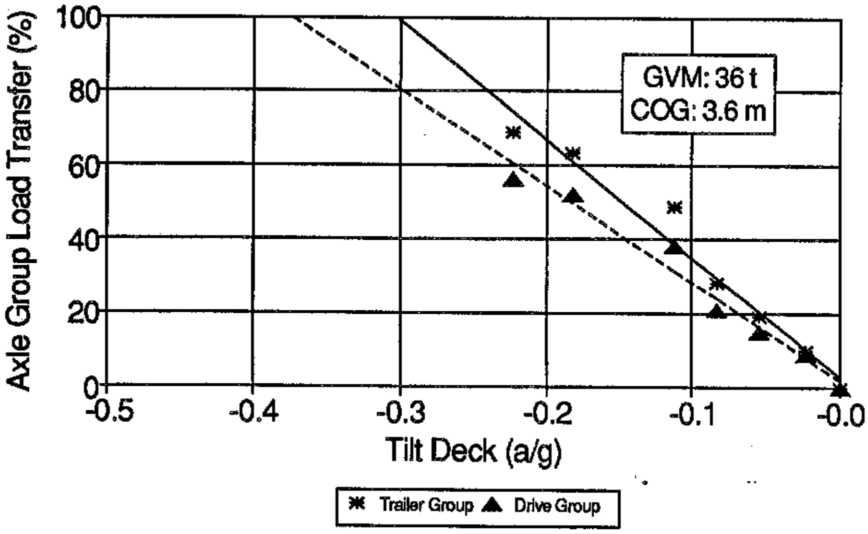
APPENDIX B

The tilt deck angle, shown as equivalent gravitational force, the projected wheel-lift points, tilt test axle loads and estimated COG heights for all test vehicles.



Roll-over Threshold Calibration

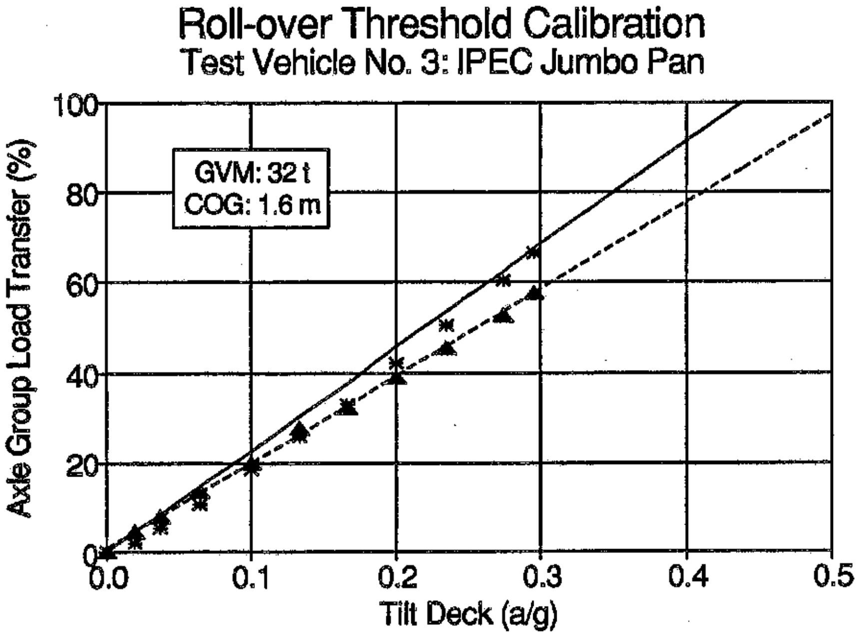
Test Vehicle No. 1: Shell Tanker

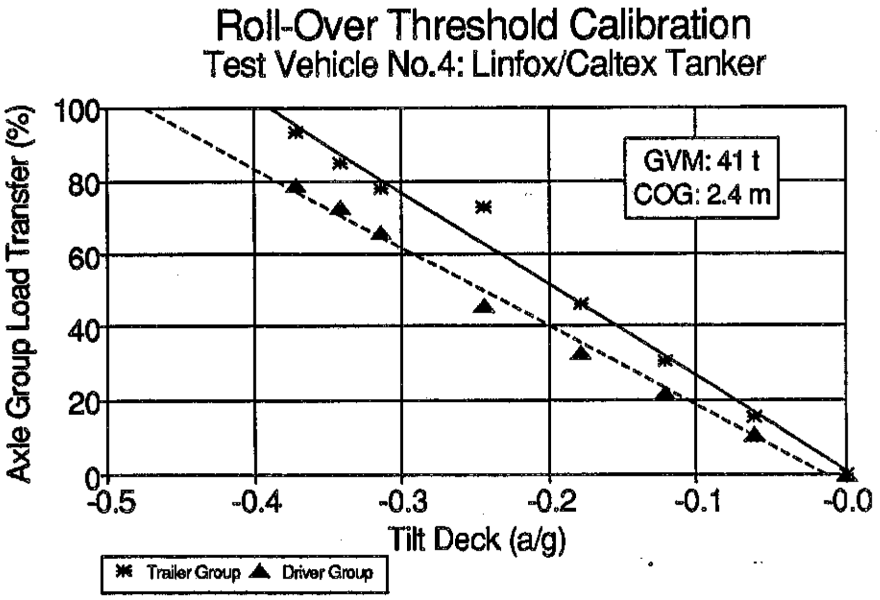


Roll-over Threshold Calibration

Test Vehicle No. 2: V/Line Freight

APPENDIX B (cont)





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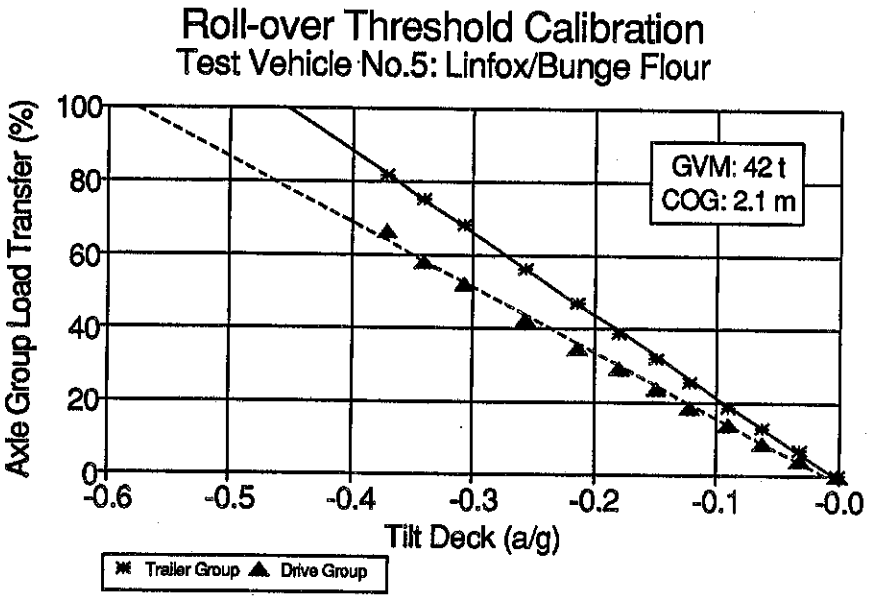


APPENDIX C

Rawlinson (1986) developed algorithms for estimating road geometry parameters from a moving vehicle. Details of the algorithms are given below.

The following assumptions are made:

1. The vehicles are driven in a conservative manner.
2. The lateral acceleration measured in the prime-mover is proportional to the roll angle of the prime-mover.

Radius of Curve:

$$r = v / \omega \qquad \text{(C1)}$$

where	r	radius (m)
	v	vehicle speed (m/sec)
and	ω	prime-mover yaw rate (radians/sec)

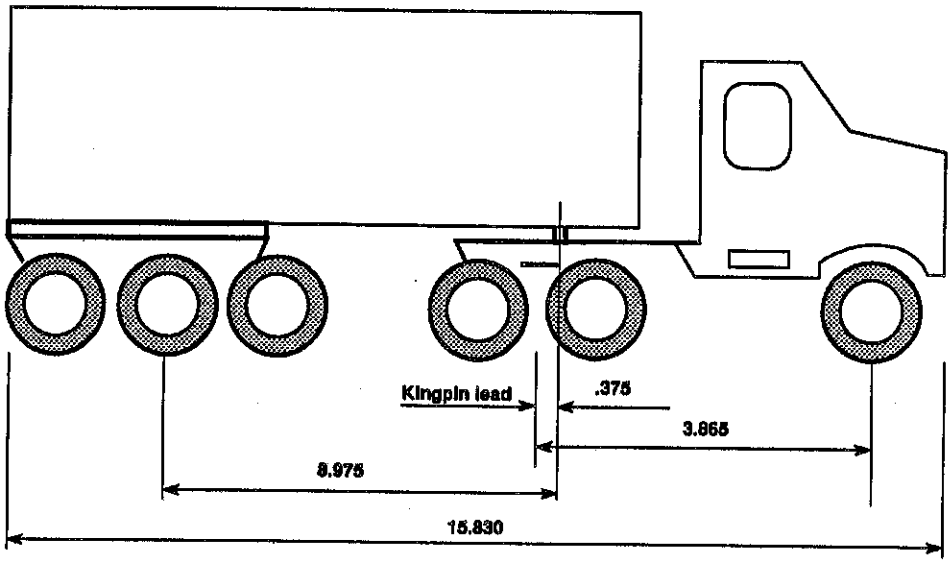
Superelevation:

$$e = 100 \times [(Rf \times a) - (v \times \omega)] / g \qquad \text{(C2)}$$

where	e	superelevation (%)
	Rf	Roll factor (ratio)
	a	lateral acceleration at the Prime-mover (m/s^2)
	g	acceleration due to gravity (m/s^2)
	v	vehicle speed (m/sec)
and	ω	prime-mover yaw rate (radians/sec)

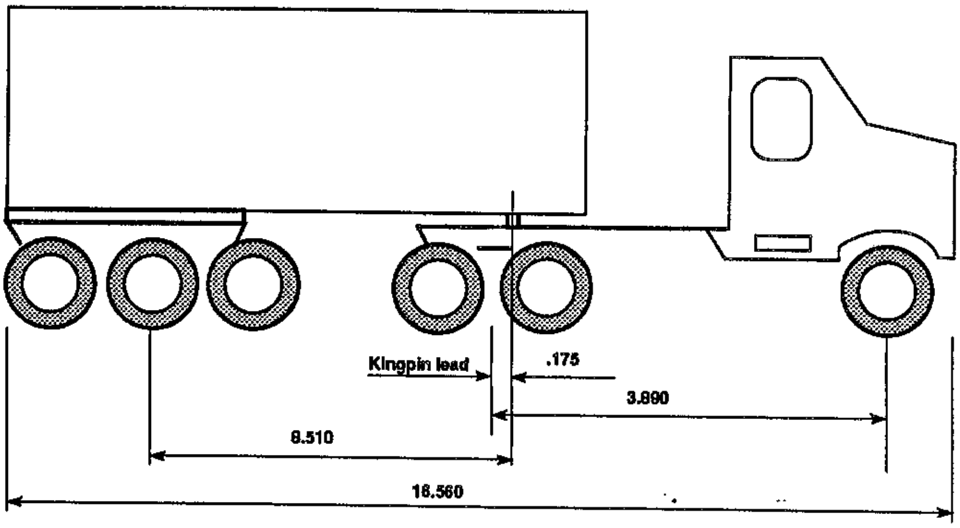
APPENDIX D

Dimensions of test vehicles



Vehicle type: Fuel tanker
Owner: Shell
Test Number: 1

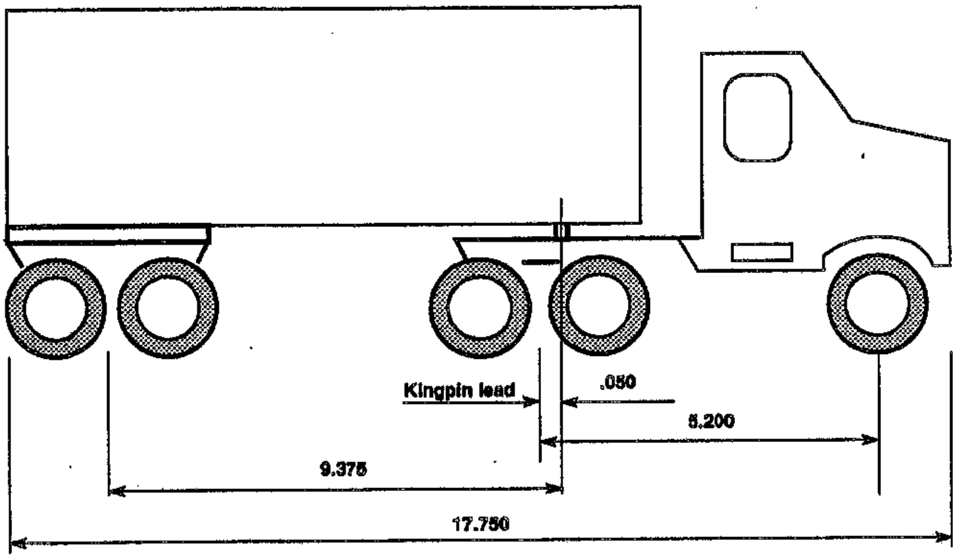
RS 035: Test Vehicle Dimensions



Vehicle type: Flatbed trailer, (freight wool)
Owner: V/line
Test Number: 2

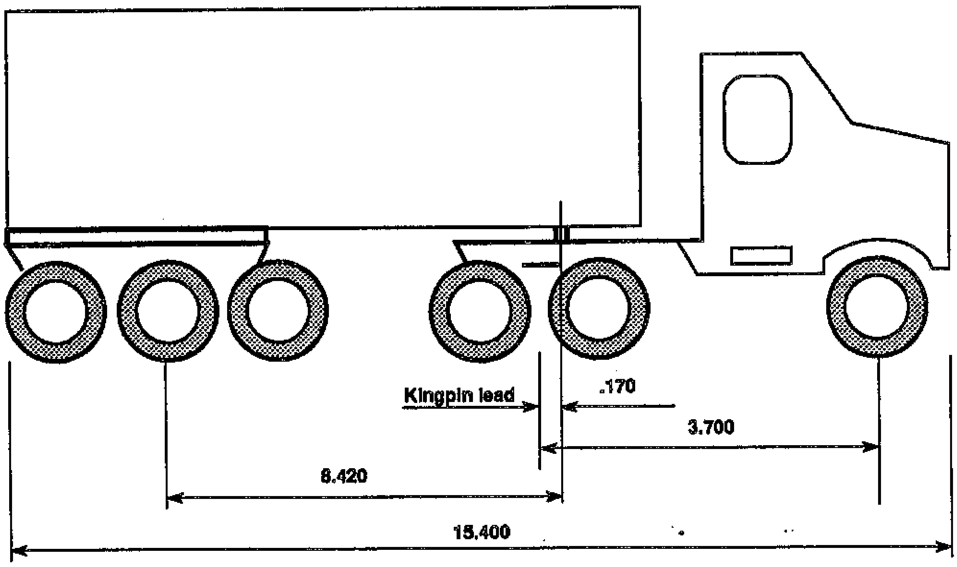
RS 035: Test Vehicle Dimensions

APPENDIX D (cont)



Vehicle type: Jumbo pan
Owner: IPEC
Test Number: 3

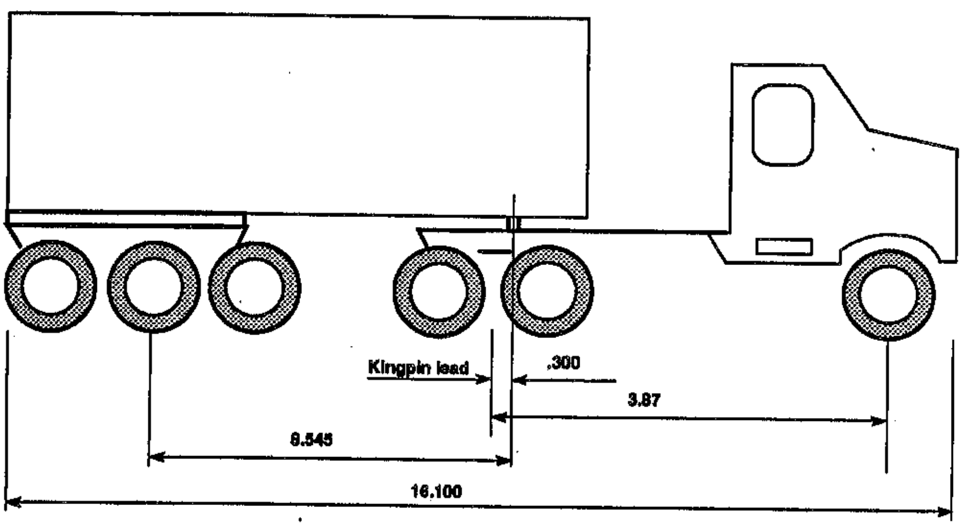
RS 035: Test Vehicle Dimensions



Vehicle type: Fuel tanker
Owner: Linfox/Caltex
Test Number: 4

RS 035: Test Vehicle Dimensions

APPENDIX D (cont)



Vehicle type: Flour tanker, pressure vessel
Owner: Linfox/Bunge
Test Number: 5

RS 035: Test Vehicle Dimensions