Behaviour of articulated vehicles on curves

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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.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 in-service characteristics of articulated vehicles as they approach the roll-threshold. The ARRB tilt deck was used to determine the roll-threshold level for each of the five test vehicles in the laden condition. The vehicle speed, the effective radius of curvature of the prime-mover travel, and the superelevation of the road surface (cross-slope) were calculated from the recorded data. Analysis of the data showed that drivers i) generally operate within a relatively narrow band of their vehicles' roll-limit (between 50 - 60%), and ii) adjust their steer path and entry speed through curves to operate within that narrow band. A relationship between the proportion of roll-threshold generated and the critical time available to advise the driver of imminent rollover has been developed.

1. INTRODUCTION

When an articulated vehicle crashes the probability of the loss of load and damage to property is high. Although the frequency of rollovers of articulated vehicles is not 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 a driver feed-back information system, a rollover warning device (RWD), 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 (Haworth et al 1991). Rollovers accounted for 858 (13%) of these crashes, of which 118 (14%) resulted in fatalities and 740 (86%) caused injury resulting in hospitalisation. Of the 6,599 fatal and hospital admission crashes, one third occurred on a curve, approximately one third occurred 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, the track width 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 rollover 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 rollover. It is reasonable to consider the first wheel lift as the stability threshold of the combination."

Therefore the experimental design for this study was: for a number of different vehicle types, measure the lateral acceleration of the test vehicle at first wheel lift (the roll-threshold), and compare it with the lateral acceleration levels during in-service operation.

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 negotiated 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 could be obtained.

4. EXPERIMENTAL VARIABLES

The rollover risk of any articulated vehicle combination is determined by the following three components:

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.

The road geometry: superelevation (cross-slope) and horizontal alignment (curvature). It is possible to estimate these with the measurement of the following variables: i) vehicle speed, ii) vehicle lateral acceleration, and iii) prime-mover yaw rate.

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.

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 driver input.

4.1 Vehicle Parameters

The following parameters were measured or estimated for each test vehicle: i) the trailer COG height - this was estimated for each laden vehicle using the tilt deck, ii) track widths - this was measured, between the centre-lines for dual tyred axles and at the tread contact area for wide single tyred axles, iii) suspension types - the suspension types fitted to both the prime-mover and the trailer were noted, iv) 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, and v) Axle masses - for each laden test vehicle the axle masses were measured and recorded.

4.2 Handling Variables

The following key parameters were measured and recorded for each test vehicle, during the in-service data collection phase of the program: i) The lateral acceleration in the cabin of the prime-mover, ii) The yaw rate in the cabin of the prime-mover, iii) 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, a method of acquiring the prime information for the RWD was assessed during the in-service 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 both chassis rails at the mid-point of the trailer suspension. The outputs from these two transducers were also recorded.

5. 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 supplied for the in-service behavioural data collection phase of the study. Table I summarises the test vehicle characteristics and dimensional details are given in Appendix A. The vehicles were fitted with the measuring instruments, calibrated on the ARRB tilt deck and returned to their depots for normal service.

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.

6. 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 pre and post-trigger events recorded either end of the logging segment. The event trigger for this series of experiments was the lateral acceleration at the prime-mover. For each test vehicle it was set around 40% of the appropriate vehicle's roll-threshold acceleration.

7. TEST VEHICLE CALIBRATION

Each test vehicle was instrumented and tested for its roll characteristics on the ARRB tilt deck in the laden condition. The oil tanker vehicles supplied 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.

TABLE I

TEST VEHICLE CHARACTERISTICS

Owner	Suspension Type Prime-mover	Suspension Type Trailer	Effective COG Height (m)	Trailer Track Width (m)	Lateral Accn. to produce wheel lift (Trailer) (g)	(Drive) (g)	Gross Vehicle Mass (GVM) (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 6x2 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

7.1 Tilt deck data

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 wheel-lift point. To estimate this limit the data obtained from the tilt deck was extrapolated to the 100% load transfer point. The tilt angle required to produce the 100% load transfer at the trailer (or the first axle group) 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 lateral acceleration (g)

Appendix B details the test vehicle roll-thresholds, where the tilt deck angle is shown as equivalent gravitational force and is plotted against lateral load transfer.

8. 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.

9. DATA ANALYSIS

From each event 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.

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

10. RESULTS

10.1 Roll-threshold Limits

Figure 1 shows the distribution of the roll-limits for all the test vehicles expressed as a percentage from the roll-threshold. This illustrates how close to the roll-threshold the test vehicles operated. The distribution is skewed to the high roll-limit as the lower level events were 'filtered' with the 40% data logger trigger. 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. This is referred to as the roll-limit.

11. NEGOTIATING A CURVE

From the first principles of physics the relationship between centripetal acceleration, radius of curvature and velocity is expressed as the following:

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

where v velocity (m/s)
r radius (m)
and a_c centripetal acceleration (m/s^2)

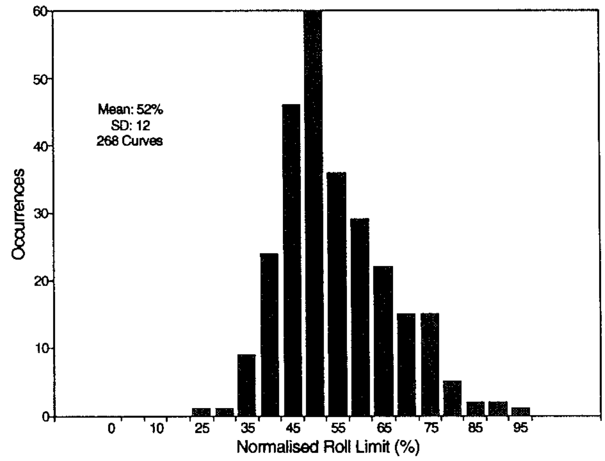

Fig. 1 - Test vehicles distribution to the roll-limit.

By applying the above expression to the data recorded around curves of less than 800 m, see figure 2, the relationship between the test vehicles' speed and the radius of curvature is obtained. The trend line is of the form:

$$v^2 = 1.42 \times r \qquad (3)$$

where v^2 velocity squared (m/s)^2
r radius (m)
and 1.42 is the acceleration coefficient (m/s^2)
with r^2 the correlation coefficient = 0.66

Information from this regression suggests that drivers negotiating curves are comfortable with, or attempt to achieve, a lateral acceleration of 1.42 m/s^2 (0.145 g) at the prime-mover.

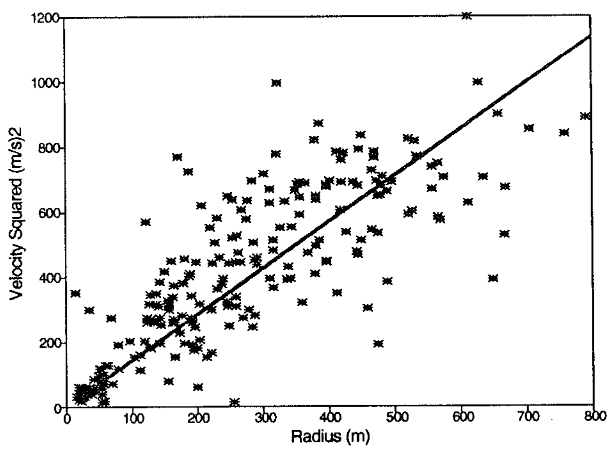

Fig. 2 - Drivers' preferred choice of vehicle speed and steer path.

11.1 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 3 is a plot of each measured event around a curve showing the time to reach each maximum lateral acceleration against the roll-limit expressed as a percentage.

The solid boxed portion at the top in figure 3, is the 'critical time window', since events that take place in this region are close to the roll-limit, within 25% of potential rollover. Events in the section labelled 'A' occur in a short time period, less than 2 seconds, these are the most critical events in terms of providing the driver with

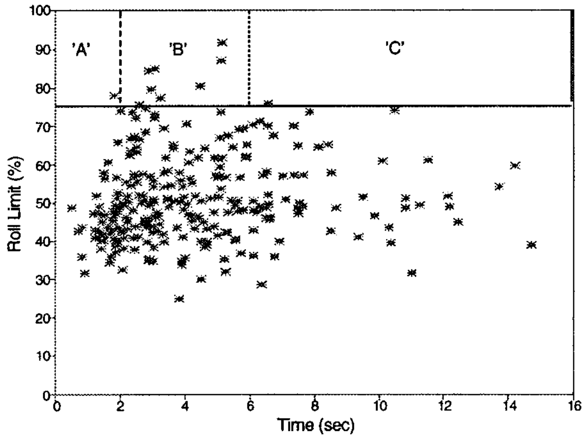

Fig. 3 - Critical recorded times to reach maximum lateral acceleration from zero or steady state acceleration.

information and time to take corrective action. Boxed area 'B' is also critical, there is however, a little more time for the driver to act, likewise events in section 'C'. For the information obtained from these five test vehicles travelling around curves, eleven events out of 269 exceeded 75% of the roll-threshold and five events were 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). Assuming that the five test vehicles are representive of the Australian fleet, it may be concluded that, on average each articulated vehicle approaches its roll-threshold approximately once every 3 days of travel (or 100 times per year).

11.2 Predicted time to rollover

The main purpose of this study was to establish the feasibility of providing the driver with advanced warning of impending instability. One of the key issues for any driver information system is - is there sufficient time for the driver to absorb the information and act?

With the above in mind, and considering the data for the events greater than 75% of the roll-threshold, analysis was carried out to predict the time from the maximum recorded lateral acceleration to the actual roll-threshold for the relevant vehicle type. A projection from the highest recorded lateral acceleration was made to the measured roll-threshold (g), and the time from the recorded maximum to the roll-threshold was used as the predicted time, see figure 4.

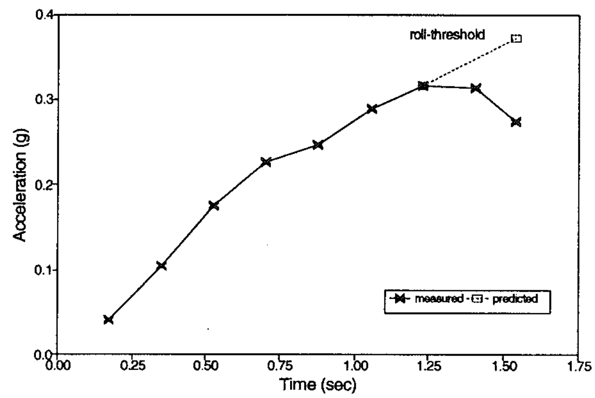

Fig. 4 - Method of predicting the time to the roll-threshold.

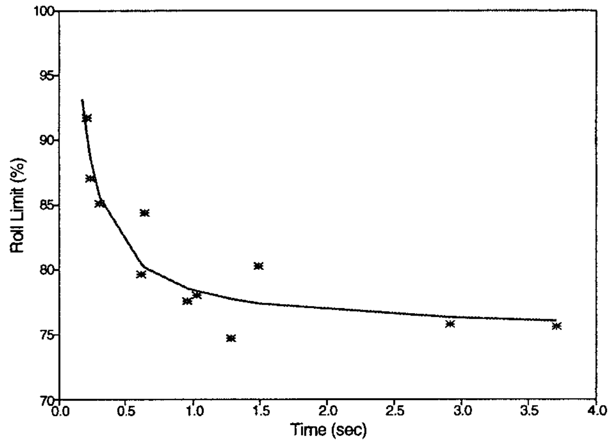

Fig. 5 - Relationship of the predicted time from the percentage of the roll-limit to the roll-threshold

Plotting the eleven events exceeding 75% of the roll-threshold, figure 5, an inverse relationship was developed predicting the available time to warn the driver.

Figure 5 demonstrates the critical times available to provide warning to drivers. Providing a warning signal when a vehicle is at 75% of its roll-limit would allow a time period of greater than 3 seconds for the driver to act. However, if the warning was presented at 85% of the roll-limit, then only less than 0.4 of a second is available.

12. DISCUSSION

12.1 Driver Warning Time

From the recorded information it appears that there is sufficient time to advise the driver when the trailer is within 25% of its roll-threshold.

12.2 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. 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.

13. CONCLUSIONS

The results from this study show:

(i) Drivers tend to adjust the vehicle speed and steer path, to negotiate curves with a high safety margin, and feel comfortable with a lateral acceleration level of 0.145 g at the cabin.

(ii) Given that the test vehicles represent a cross-section of Australian vehicles, on average an articulated vehicle exceeds 80% of its roll-threshold limit once every 3 days.

(iii) There is a defined inverse relationship between a vehicle's percentage of the roll-limit and the time available to advise the driver that rollover is imminent.

(iv) In all of the cases studied, assuming that the first warning started at a point 25% from the roll-threshold, there is sufficient time to provide the driver with feedback information to alert them that the trailer is approaching the rollover 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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APPENDIX A
Test vehicle dimensions.

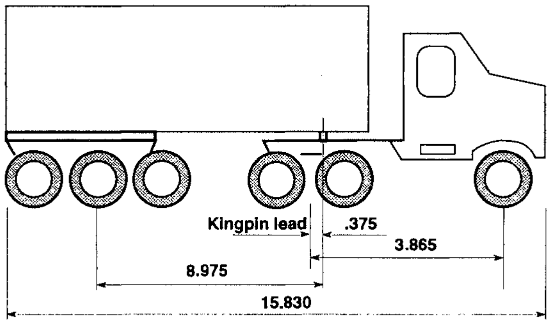

Fig. A1 - Vehicle dimensions for the Shell fuel tanker.

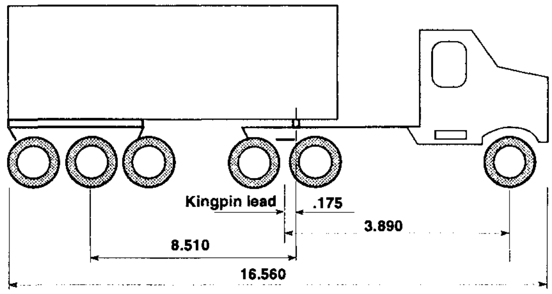

Fig. A2 - Vehicle dimensions for the V/Line flatbed trailer (Wool).

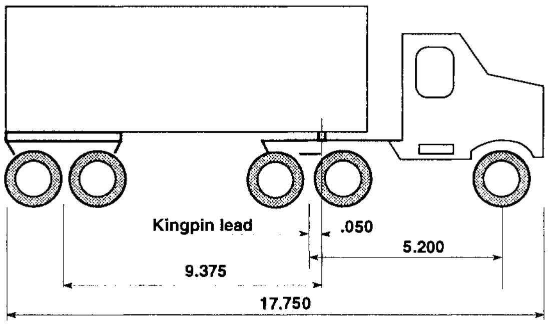

Fig. A3 - Vehicle dimensions for the IPEC pantechnicon.

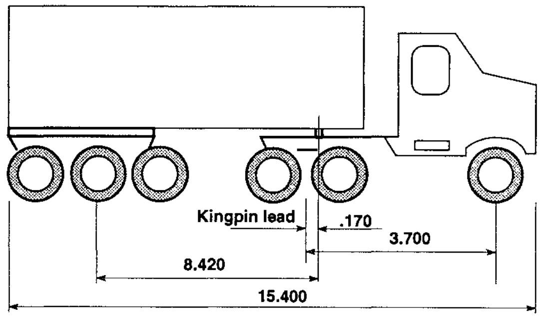

Fig. A4 - Vehicle dimensions for the Linfox fuel tanker.

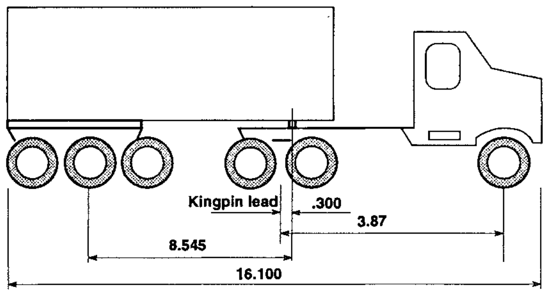

Fig. A5 - Vehicle dimensions for the Linfox flour tanker .

APPENDIX B

The roll-threshold calculations for each test vehicle. The tilt deck angle is shown as the equivalent gravitational force (a/g).

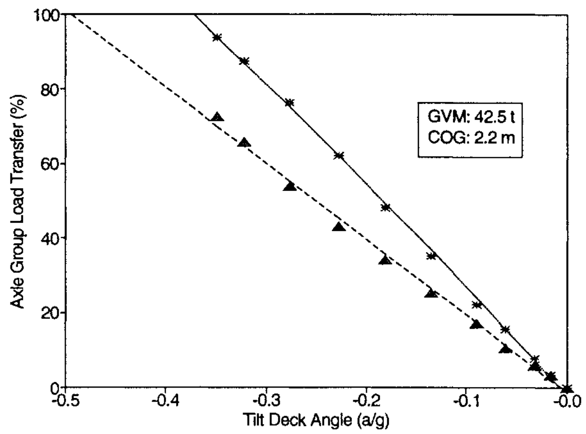

Fig. B1 - Roll-threshold calibration for the SHELL fuel tanker.

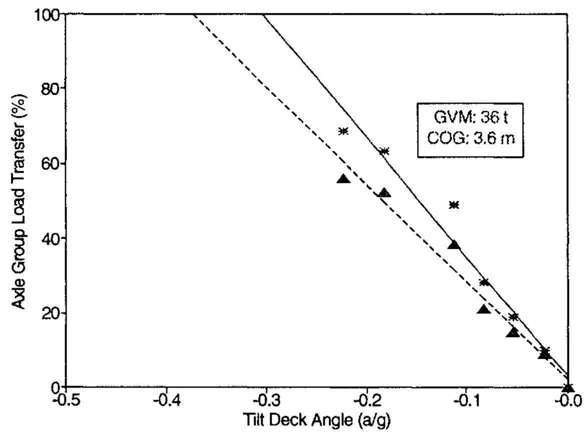

Fig. B2 - Roll-threshold calibration for the V/Line flatbed trailer (Wool).

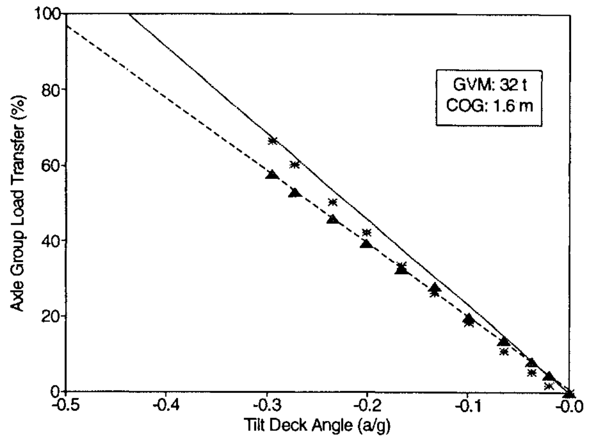

Fig. B3 - Roll-threshold calibration for the IPEC pantechnicon.

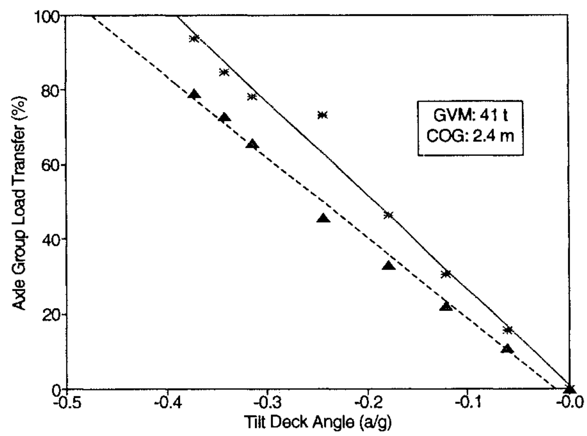

Fig. B4 - Roll-threshold calibration for the Linfox fuel tanker.

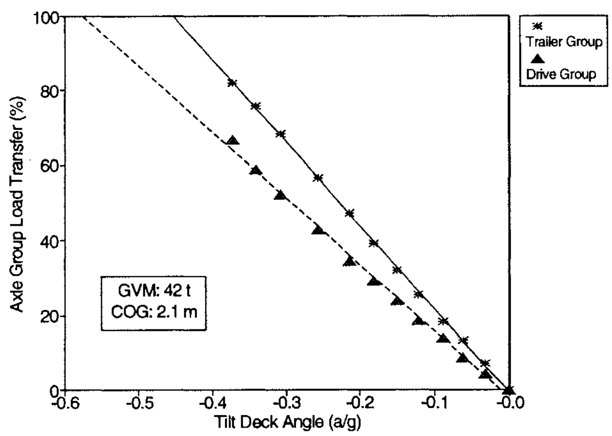

Fig. B5 - Roll-threshold calibration for the Linfox flour tanker.