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STABILITY OF OVER-HEIGHT LOW-DENSITY FREIGHT VEHICLES AND ITS PREDICTION

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ABSTRACT

Operators carrying low density freight usually operate vehicles with axle-loads below the allowable legal limit. To maximise the productivity of these vehicles, the cubic capacity is maximised. Already, tandem axle dropwell B-Doubles have been adopted by some operators and the use of these vehicles with a 4.6m rather than 4.3m height restriction has been proposed. The stability of these higher vehicles was investigated and a prediction model was also developed.

Several dropwell semi-trailer vehicles, at heights of 4.3m and 4.6m, were tested on the tilt deck at ARRB Transport Research (ARRB TR) to determine their static roll threshold. The vehicles were loaded with products of different densities and the load height was varied to provide comparison.

A prediction formula for roll threshold (lateral acceleration producing first wheel lift) was developed from an existing method for computing the stability factor. The lateral shift in the position of the vehicle's centre of gravity, which is due to the sprung mass roll angle, adds a further overturning moment to the vehicle. This effect is included in the prediction model.

All of the 4.6m high vehicles tested produced static roll thresholds above the target value, and the prediction model based on data from vehicles tested was found to be accurate to within ±7% of the tested values. The vehicle tested with the lead B-Double trailer, a practice not used in operation, was the only exception due to the load being largely located towards the front of the trailer. The model was used to predict the roll threshold for a "worst case" vehicle based on homogenous loading that produced maximum legal axle loads. This vehicle was borderline on the target value. Since homogenous loading is not practically possible, it was concluded that 4.6m high vehicles with low density freight would have acceptable stability.

The implications of these findings should see the emergence of these 4.6m high vehicles into industry, which will ultimately increase productivity and efficiency of freight transportation.

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1. INTRODUCTION

The roll stability of vehicles is one of the most important measures of vehicle safety. With the advent of new configurations of vehicles that are longer, wider and higher, conventional methods of evaluating stability are proving to be more difficult and expensive. The stability of a vehicle unit as a whole is influenced by a range of parameters, these include suspension characteristics, spring and tyre spacings, centre-of-gravity height, type of connection between individual units, to name a few. In Australia, B-Doubles have become increasingly common, though as yet, there is no facility to measure the roll stability of these combinations. B-Triples are currently being trialed and are typically 33% longer than B-Doubles. These types of vehicles are of particular interest as each individual unit is roll-coupled, thus producing a situation where if one trailer is about to roll-over, resistance is provided by the other units.

There has been a recent push in Australia to increase the maximum legal height of heavy vehicles from 4.3m to 4.6m for cubic low-density loads that do not impinge upon the maximum legal mass limits. This further substantiates the need to provide a quick and accurate method for the prediction of vehicle stability. A screening method was originally proposed (George et. al., 1996) to use the gross combination mass (GCM) of a vehicle as a guide to roll threshold, which is briefly examined in this report and found to have limitations.

The prediction of vehicle stability is usually compounded by the need to obtain difficult parameters such as suspension roll stiffness. This paper presents a prediction method for vehicle stability, using relatively easily obtained parameters and providing higher accuracy than the methods reviewed. This prediction method was developed as a screening technique for vehicles that could be utilised by enforcement officers on the spot using parameters that were known or easily measured. This method has been compared against stability tests on vehicles conducted on the tilt table facility at ARRB TR.

2. METHOD

2.1 Full-Scale Tests

The roll stability of several semi-trailers was measured using the ARRB TR tilt table to raise one side of the vehicle until one-side of one axle-group reached zero load. In each tilt test the trailer group was the first to reach wheel lift.

The roll thresholds and the centre of gravity (CoG) heights were determined by tilting the vehicle and recording the tilt angles and the change in axle loads. The roll threshold is defined as ***"the tilt angle, expressed as the fraction of gravitational force, to produce wheel-lift on any axle group***". In general, wheel lift first occurs at the trailer axle group for a semi-trailer.

The effective vehicle CoG height was calculated with Eqn 1, using the recorded data from the tilt test such as change in axle load, tilt deck angle, and vehicle track width. This method for computing CoG height is accurate over a range of tilt angles as the rate of load transfer is used instead of absolute load transfer. This method is sourced from Bedard (1986).

$$CoG = -\frac{T}{W}\left(F_o \tan\theta + \frac{1}{\cos\theta}\frac{dF}{d\theta}\right) \qquad (1)$$

where:

CoG = effective vehicle CoG height (m);
T = weighted vehicle track width (m);
W = total supported load (on side being lifted) (t);
F_o = initial tyre to ground contact load (t);
θ = tilt angle (radians);

The roll threshold of the vehicle is obtained directly from accelerometers attached to the tilt deck.

2.2 Roll-Threshold Prediction (Empirically Based Formula)

The CoG height and the roll threshold were predicted using an adaptation of the method outlined in Winkler et al (1992). The CoG height (H) is predicted using Eqn 2, which is subsequently used in Eqn 3 to predict the roll threshold (a_y). The factor (F) described by Eqn 4 was empirically derived and approximated the lateral shift of the sprung mass CoG that occurs with increasing body roll angle. This lateral shift has the effect of decreasing the roll threshold and is dependent on the suspension characteristics, which are indirectly accounted for by Eqn 4.

$$H = \frac{H_e W_e + H_p W_p}{W_e + W_p} \qquad (2)$$

where:

H = vehicle CoG height (m);
H_e = CoG height of empty unit (m);
W_e = weight of empty unit (N);
H_p = CoG height of payload (m);
W_p = weight of payload (N).

$$A_y = \frac{T}{2HF} \qquad (3)$$

where:

A_y = roll threshold (g);
T = weighted track width (m);
H = vehicle CoG height (m) (from Eqn. 2);
F = correction factor.

$$F = 1 + \frac{W_p(H_p - H_e)}{H(W_e + W_p)} \qquad (4)$$

2.3 Theoretical Prediction Formula

Examining the phenomena of roll threshold from first principles and theory, one can derive the formula presented as Eqn 5 (**Appendix A** contains the derivation).

$$A_y = \frac{T}{2H\left[1 + \frac{W_p(H_p - H_{rc})(H - H_{rc})}{H(K_f - W_p(H_p - H_{rc}))}\right]} \qquad (5)$$

where:

H = vehicle CoG height (m);
T = weighted vehicle track width (m);

W_p = weight of payload (N);
H_{rc} = height of suspension roll-centre (m);
K_f = suspension roll stiffness (Nm/rad).

The suspension roll stiffness is a difficult parameter to estimate for individual vehicles. Substituting Eqn 4 into Eqn 3 results in a formula with similar form to Eqn 5, and as such, the similar terms can be equated to provide an expression that can be solved for the suspension roll stiffness as shown in Eqn 6.

$$K_f = (H_p - H_{rc})\left[W_p + \frac{(H - H_{rc})(W_e + W_p)}{(H_p - H_e)}\right] \qquad (6)$$

Eqn 6 indicates that as the vehicle mass increases and/or the CoG height increases, the suspension roll stiffness also increases. As the vertical load increases, most non-linear suspensions are designed to increase vertical stiffness, and therefore increase roll stiffness. A further simplification of Eqn 6 using the assumptions that $H_e \approx H_{rc}$ and $(H - H_{rc}) \approx (H_p - H_{rc}) \approx 1$, results in Eqn 7. In this simple form, it is clear that the suspension roll stiffness is a function of the vehicle mass.

$$K_f = 2W_p + W_e \qquad (7)$$

A comparison between the theoretically based (Eqn 5) and empirically based (Eqn 3) formulae of the roll threshold predictions for the vehicles tested, revealed that the empirically based formula produced more accurate roll threshold predictions. This can be attributed to the lower number of equation parameters that are simpler to accurately obtain, and the relationship that appears to exist between suspension roll stiffness (K_f) and the parameters shown in Eqn 6. The empirical prediction method therefore assumes this relationship for suspension roll stiffness (Eqn 6), which obviously influences vehicle roll threshold, holds true for all heavy commercial vehicles. All predicted results in this paper have been calculated using the empirically based formula (Eqn 3).

3. TEST VEHICLES

A range of semi-trailers has been tested on the tilt table, using a variety of trailer types, such as dropwell trailers, flatbed trailers and the lead trailer from a B-Double configuration. The load types and heights of the test vehicles have also been varied. The vehicles with the cement and insulation loads were loaded such that the high density cement was in the dropwell section of the trailer, while the low density insulation was loaded above that. This represents a "best case" loading in that vehicle's CoG height would be minimised due to the distribution of the mass within the trailer. A "worst case" loading is a homogenous load occupying all of the trailer's cubic capacity. High density products are very rarely, if ever, placed on top of low density products. Table I lists some details about the test vehicles and the loads.

Table I: Vehicle Details

Vehicle Code	Vehicle Type	Trailer Type	Load Type	Load Density (kg/m^3)	Load Height (m)
KW1	A122	Dropwell (Lead)	Cement & Insulation	691 & 66	4.6
KW2	A122	Dropwell	Cement & Insulation	691 & 66	4.6
VO1	A112	Dropwell	Cement & Insulation	691 & 66	4.6
VO2	A112	Dropwell	Cement & Insulation	691 & 66	4.6
ME1	A122	Dropwell	Cement & Insulation	691 & 66	4.6
HD	A122	Dropwell	Cereal	151	4.6
MD	A122	Dropwell	Paper Products	104	4.6
3.4m	A122	Dropwell	Paper Products	129	3.4

3.7m	A122	Dropwell	Paper Products	127	3.7
4.0m	A122	Dropwell	Paper Products	126	4.0
4.3m	A122	Dropwell	Paper Products	124	4.3
PR	A123	Flatbed	Newsprint Rolls	663	4.3
Con	A122	Flatbed	Paper Products	145	4.3
Hay	A122	Flatbed	Hay	229	4.4

4. RESULTS

4.1 Measured Roll-Thresholds

Two full tilt tests were conducted on each vehicle combination. The measured and predicted roll threshold results are listed in Table II for each of the tested vehicles.

TABLE II: Tilt Test Results and Predictions

Vehicle Code	Load Density (kg/m^3)	Measured Roll Threshold (g)	Predicted Roll Threshold (g)	Error (%)
KW1	691 & 66	0.49	0.57	17.0
KW2	691 & 66	0.52	0.52	-0.1
VO1	691 & 66	0.53	0.51	-3.3
VO2	691 & 66	0.49	0.50	3.3
ME1	691 & 66	0.55	0.52	-4.7
HD	151	0.36	0.35	-2.1
MD	104	0.41	0.40	-3.8
3.4m	129	0.48	0.50	3.7
3.7m	127	0.47	0.45	-4.3
4.0m	126	0.44	0.43	-1.8
4.3m	124	0.43	0.40	-7.0
PR	663	0.33	0.34	1.2
Con	145	0.34	0.32	-4.0
Hay	229	0.29	0.30	2.4

4.2 Predicted Roll-Threshold

The vehicle roll thresholds were predicted using Eqn 3 as outlined in Section 2. Table II lists the predicted roll thresholds and the error when compared to the measured. These results indicate that the prediction method provides a good estimate of the roll thresholds of vehicles with various load types and distributions. Estimates of the roll thresholds for the tested vehicles are within ± 7% of the measured values, though most are within ±5%. Vehicle KW1, the only vehicle using the lead trailer of a B-Double unit, is the only exception and this is due to the large amount of load distributed to front of the trailer causing the longitudinal bias of this configuration. It is also interesting to note that most of the predictions are on the conservative side of the measured roll thresholds, which is desirable.

5. DISCUSSION

5.1 Predicted Roll-Thresholds

Since the prediction method has shown to be quite accurate for the tested vehicles, it is reasonable to extend this method to B-Double vehicles. Table III lists the predictions for a 4.6m high B-Double with dropwell trailers carrying a variety of loads types and densities.

Table III: Predicted roll-threshold for a B-Double

Load Type	Mean Load Density (kg/m^3)	% of Max. GCM	Predicted RT (g)
Cement & Insulation	129*	83	0.50
Homogenous	129	83	0.34
Homogenous (80% GCM)	122	80	0.34
Homogenous (90% GCM)	152	90	0.32
Homogenous (100% GCM)	183	100	0.30
Cereal	154	91	0.32
Cereal	151	90	0.32
Paper Products	104	75	0.36
Homogenous (0.33g)	138	86	0.33

- Cement at the bottom (691 kg/m^3) and insulation at the top (66 kg/m^3)
-

Figure 1 shows the roll threshold predictions for typical dropwell B-Doubles carrying loads with varying densities. The points joined by the line were predicted for a pure homogenous load in a typical dropwell B-Double. A homogenous load will produce the "worst case" conditions as typical operating loads are usually more dense to the bottom therefore lowering the vehicle's CoG height and effectively increasing the roll stability. The outlying point was the prediction for a vehicle loaded with high density cement at the bottom and low density insulation at the top whose mean load density was 129kg/m^3. It is clear from this figure that the GCM is not a good measure of roll threshold, and that homogenous loading will considerably lower the roll threshold.

The roll threshold of a vehicle is mainly dependent on the CoG height of the vehicle. The CoG height is dependent on many parameters such as load type, load density, load distribution, and deck height. In the case of a B-Double carrying the non-homogenous load of cement and insulation, the CoG height was approximately 1.45m when calculated using the densities of the individual load products. Based upon the total payload divided by the total volume, the average density of this load was approximately 129 kg/m^3, which would produce a CoG height of approximately 1.89m.

Vehicles rarely carry a truly homogenous load and for a certain GCM, many loading conditions can apply that affect the CoG height and ultimately the roll threshold. Predictions of roll threshold for typical dropwell B-Doubles (see Table III) indicate that the proposed target roll threshold of 0.33g (George et. al, 1996) can be achieved with a homogenous load density of approximately 138kg/m^3. This density corresponds to 86% of maximum legal GCM and a CoG height of approximately 1.9m.

The lead trailer (Vehicle KW1) exhibited a higher roll threshold than that achieved by the tag trailer (Vehicle KW2). The overall vehicle roll stability is not a simple average of the stability of individual units. A complex relationship exists between the roll threshold of individual vehicle units and fully connected vehicles. It is important to note that the longitudinal load distribution will affect the axle loads and the roll threshold, as can be seen with the vehicle connected to the lead B-Double trailer (Vehicle KW1).

The non-homogenous loads used in the tests (cement and insulation), produced roll-thresholds better than the proposed 0.33g target. Results produced by the steel suspended tandem-drive vehicle were very similar to those for the air suspended tandem-drive. The steel suspended single drive vehicle (VO1) produced results slightly better than those achieved by the single drive with air suspension (VO2). Unfortunately, the roll stiffness of the tested vehicles were not available and it is difficult to draw any conclusions.

Vehicle HD (semi-trailer with cereal products) produced a roll threshold of 0.36g, which was slightly lower than the 0.41g roll threshold produced by vehicle MD (semi-trailer with paper goods). Vehicle HD was at 83% of maximum allowable GCM (39t for an A122 semi-trailer) and produced the lowest roll threshold of all the tested vehicles. However, the roll threshold was better than the proposed target value of 0.33g. A typical dropwell B-Double loaded with a similar configuration would represent 90% of GCM and is predicted to have a roll threshold of 0.32g.

6. CONCLUSIONS

- The prediction method was found to produce roll threshold results accurate to ±7% for vehicles with a variety of load densities and configurations;

- Using the GCM as a means of checking compliance to an agreed roll threshold is **<u>not</u>** robust;

- The vehicles laden with non-homogenous loads represented a “best case” loading configuration from a stability perspective, while the maximum legal mass homogenous loads represented a “worst case” loading configuration. Consequently, the "best case" vehicles exhibited excellent roll thresholds and exceeded the proposed roll threshold target value of 0.33g due to large variation in product density;

- A typical dropwell B-Double carrying low density, homogenous products is predicted to produce roll thresholds better than the 0.33g target, for GCM of less than 86% of the current maximum allowed.

- The tested vehicles with homogenous loads of varying densities (filled to cubic capacity) produced roll thresholds ranging from 0.41g to 0.29g.

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7. REFERENCES

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AUTHOR BIOGRAPHIES

Matt Elischer joined ARRB TR in May 1996 after graduating from Royal Melbourne Institute of Technology (RMIT) with a Bachelor of Mechanical Engineering (Hons). He works in the Heavy Vehicles and Mining area, where he is heavily involved in computer modelling and simulation. Matt also investigates heavy vehicle dynamics and performance assessment, a component of this work is data interpretation and analysis.

Hans Prem has a Bachelor's degree and a Ph.D. in Mechanical Engineering from the University of Melbourne, which he received in 1979 and 1984, respectively. His interests are principally in vehicle dynamics and road roughness research. Hans first joined ARRB Transport Research in 1984, and was responsible for development of the prototype version of the ARRB laser profiler. In 1989 Hans left ARRB TR to take up a position in BHP Research, as a specialist in heavy haulage vehicles in mining equipment research. Hans returned to ARRB TR in 1997, where he is Research Coordinator of the Heavy Vehicles and Mining business area.

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Appendix A – Derivation of Theoretical Prediction Formula

The derivation of an expression for roll threshold (the steady state lateral acceleration required to produce the lift off of one side of the ***first*** axle group) is shown in this appendix. **Figure A-1** displays the forces involved as a vehicle rolls during a steady state turn

The following definitions are used throughout the derivation:

T = weighted track width (m);
W_p = weight of payload (N);
H_p = height of payload CoG (m);
H_{rc} = height of sprung mass roll-centre (m);
W_e = weight of empty unit (N);
H_e = height of empty unit CoG (m);
H = height of overall CoG (m);
A_y = lateral acceleration (g);
K_ϕ = suspension roll stiffness (Nm/rad);
ϕ = sprung mass roll angle (rad);
F_y = lateral tyre force (N);
RC = suspension roll-centre;

The following assumptions are used in the derivation:

$g = 9.807$ m/s^2;
Sprung mass is approximately equal to the payload mass;
$H_e \approx H_{rc}$;
$\sin\phi \approx \phi$, at small body roll angles (up to 10°);
No lateral offset in centre of masses;

Summing moments around point O:

$$W_p H_p A_y + W_p \sin\theta \left(H_p - H_{rc}\right) + W_e H_e A_y + W_e \sin\phi \left(H_{rc} - H_e\right) = \left(W_p + We\right)\frac{T}{2}$$

After manipulation and simplification (using Eqn 2 in section 2.2):

$$A_y = \frac{T}{2H} - \sin\phi\left[1 - \frac{H_{rc}}{H}\right] \qquad \text{(A-1)}$$

An expression for the roll angle, ϕ, can be obtained by calculating the total roll moment supported by the suspension, and introducing a suspension roll stiffness, K_ϕ. Summing moments about the suspension roll-centre, RC, gives:

$$W_p A_y\left(H_p - H_{rc}\right) + W_p \sin\phi \left(H_p - H_{rc}\right) = K_\phi \phi$$

This solves for ϕ.

$$f = \frac{W_p A_y (H_p - H_{rc})}{[K_f - W_p (H_p - H_{rc})]} \qquad \text{(A-2)}$$

Substituting Eqn III-2 into Eqn III-1 yields the following:

$$A_y = \frac{T}{2H} - A_y \left(\frac{W_p (H_p - H_{rc})}{K_f - W_p (H_p - H_{rc})} \right) \left(1 - \frac{H_{rc}}{H} \right)$$

Solving for A_y produces:

$$A_y = \frac{T}{2H \left[1 + \frac{W_p (H_p - H_{rc})(H - H_{rc})}{H (K_f - W_p (H_p - H_{rc}))} \right]} \qquad \text{(A-3)}$$

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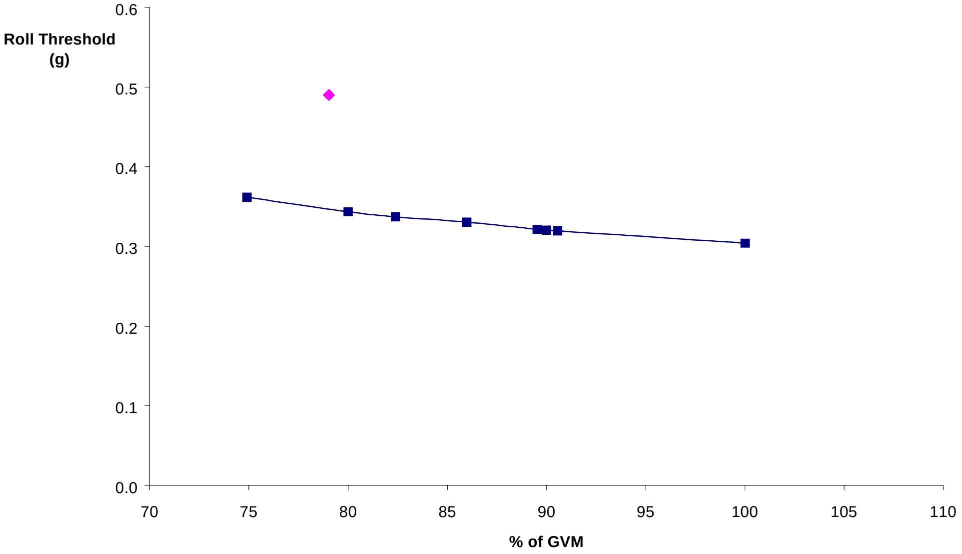

Fig 1: Percentage of maximum GCM against Roll Threshold for B-Doubles

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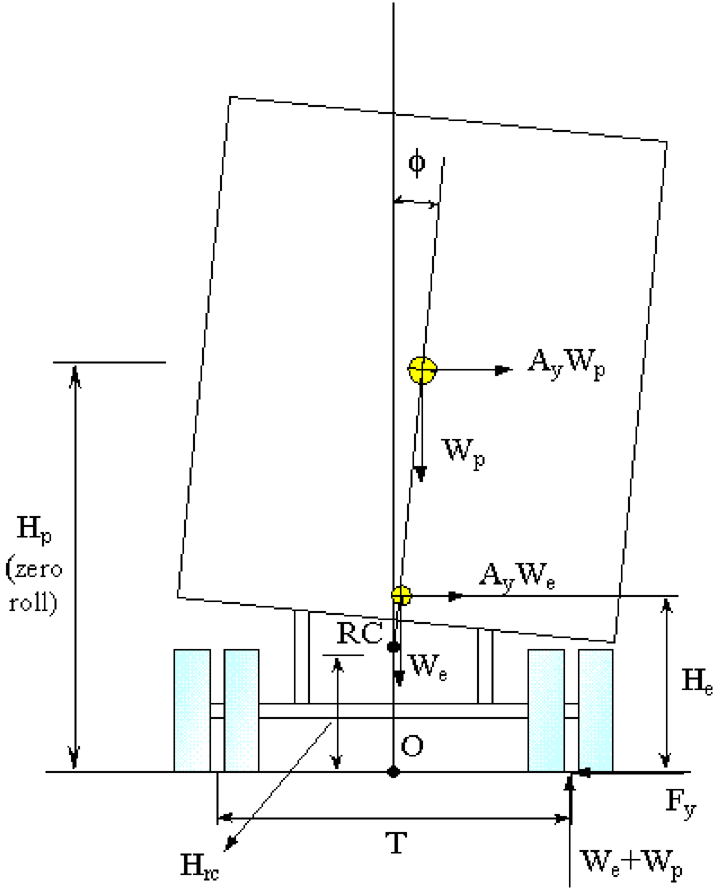

Figure A-1: Sprung mass roll during steady-state turn at wheel lift