STABILITY ENHANCEMENT OF A VERY MANOEUVRABLE VEHICLE COMBINATION

David White

DSIR, IDA

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Breaking the Stability - Manoeuvrability Compromise

By DAVID WHITE

Abstract

The compromise between stability and manoeuvrability is presented and illustrated using results from stability analysis of typical New Zealand vehicles. Beginning from a typical A-train, various strategies for improving its stability are discussed. The advantages and disadvantages of B-trains, S-trains, purpose-designed A-trains and alternative hitch connections are outlined. One particular alternative hitch connection, employing a speed-sensitive drawbar, is highlighted for further research. Theoretical results indicate that its stability and manoeuvrability are independent: there is no compromise of one with the other.

Further stability parameters are introduced to New Zealand (Yaw Damping Ratio, Low-Speed Transient Offtracking and High-Speed Steady-State Offtracking). A comprehensive table of stability results is given for a wide range of NZ vehicles.

The inferior stability of three-axle trucks towing two- or three- axle dog trailer is highlighted.

A case study reveals the stability and manoeuvrability of triaxle semitrailers with varying degrees of steerability of the rearmost axle. By varying the stiffness of the steering system with forward speed, the good stability of the fixed triaxle arrangement is retained while allowing manoeuvrability approaching that of a freely-castoring axle.

Research Engineer
DSIR, Industrial Development, Auckland

Introduction

Life is full of compromises. Virtually every purchase we make involves compromising quality with price. Modern heavy vehicle combinations at the upper limits of combination mass and overall dimensions tend to be "stable" or "manoeuvrable" or a compromise of the two (Figure 1). For example, the B-train, which has very good high-speed stability is poor when it comes to low-speed manoeuvrability. Conversely, the A-train's stability is poor, while its manoeuvrability is good.

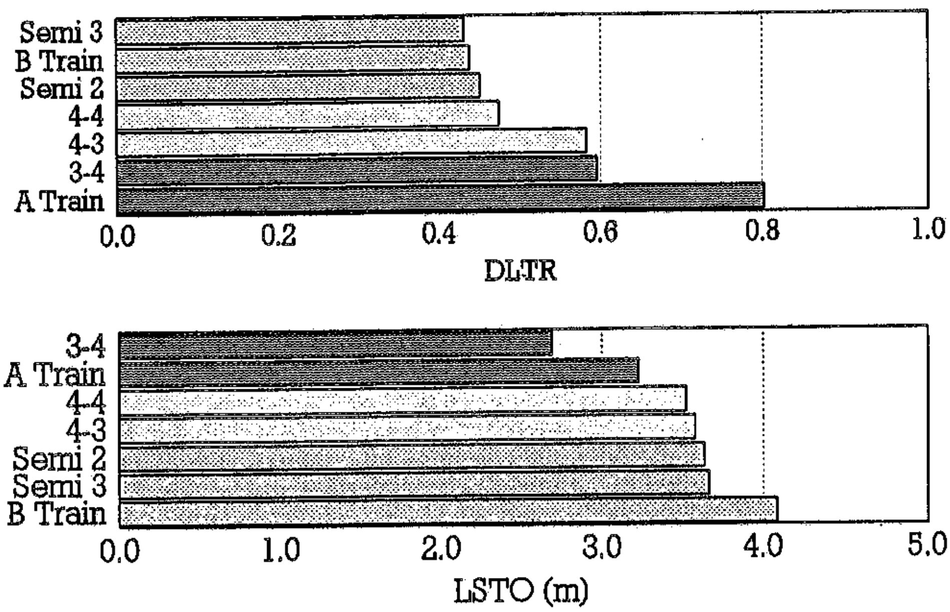

Figure 1
The Compromise between Stability and Manoeuvrability

Improving Stability of A-Trains

Typical A-Train Performance

Let us consider the A-train. While its inherent stability deficiencies have been rightly publicised (in this country it was at the first IRTENZ International Seminar[1]), the A-train does have some commendable features which suit it to certain operations. For example, the tight turning capability, and the ease of coupling and uncoupling the rear trailer.

Figures 2 to 7 indicate the stability and manoeuvrability performance of a range of typical NZ heavy vehicle configurations. Each vehicle is simulated as operating at its maximum legal GCM, with a typical load of uniform density. The A-train is 39 tonne GCM.

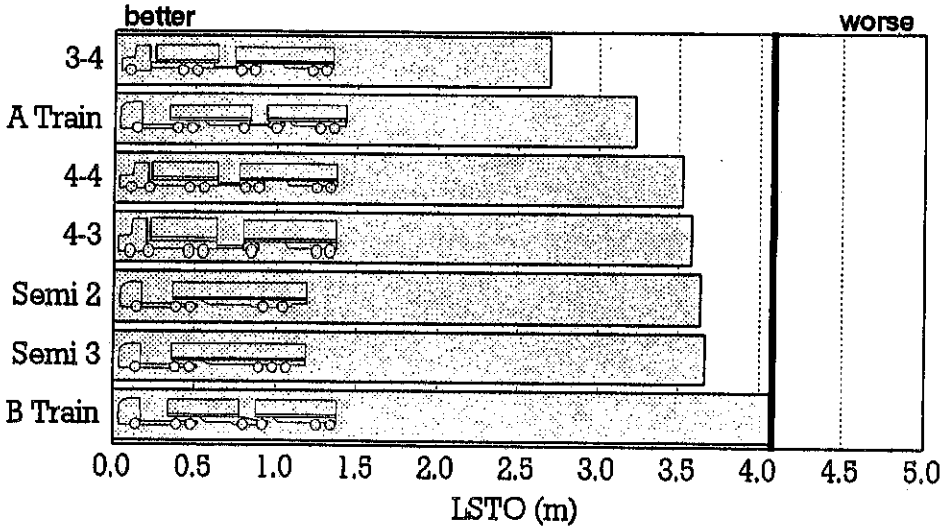

Figure 2
LOW-Speed Transient Offtracking Results for Typical NZ Vehicles

The Low-Speed Transient Offtracking (LSTO) results indicate the manoeuvrability of a combination in a specific 90 degree turn. Further details regarding LSTO are given in Appendix B. Figure 2 indicates that the A-train is one of the more manoeuvrable combinations.

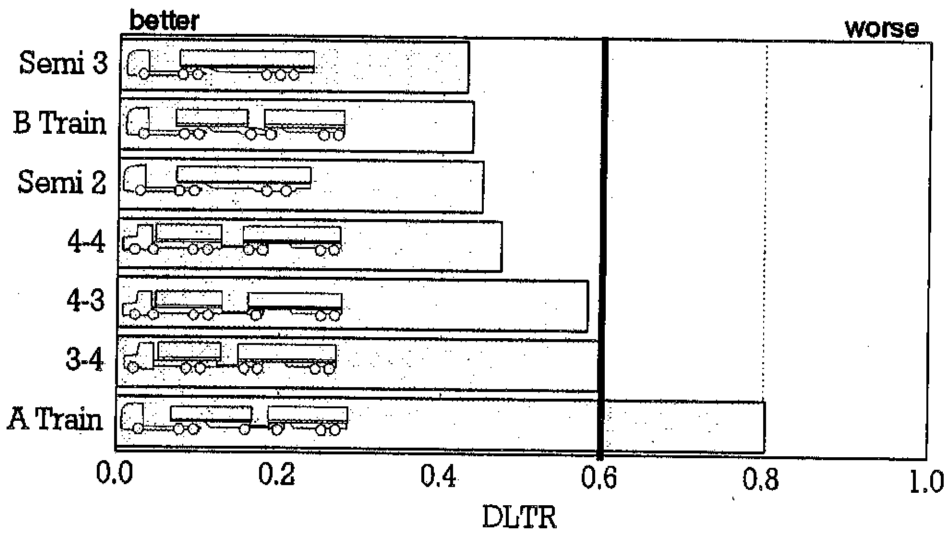

Figure 3
Dynamic Load Transfer Ratio Results for Typical NZ Vehicles

The only stability parameter in which some typical NZ vehicles fail to reach the recommended performance target is the Dynamic Load Transfer Ratio (Figure 3). DLTR indicates how close a rig gets to rolling over during a standard highway-speed manoeuvre. If DLTR=1 then the combination in question managed to lift the wheels off on one side. (The drawbar trailer for truck-trailers and A-trains is evaluated separately, since it can roll over without overturning the prime mover.) Of the main vehicle configurations, the A-train is the worst performer.

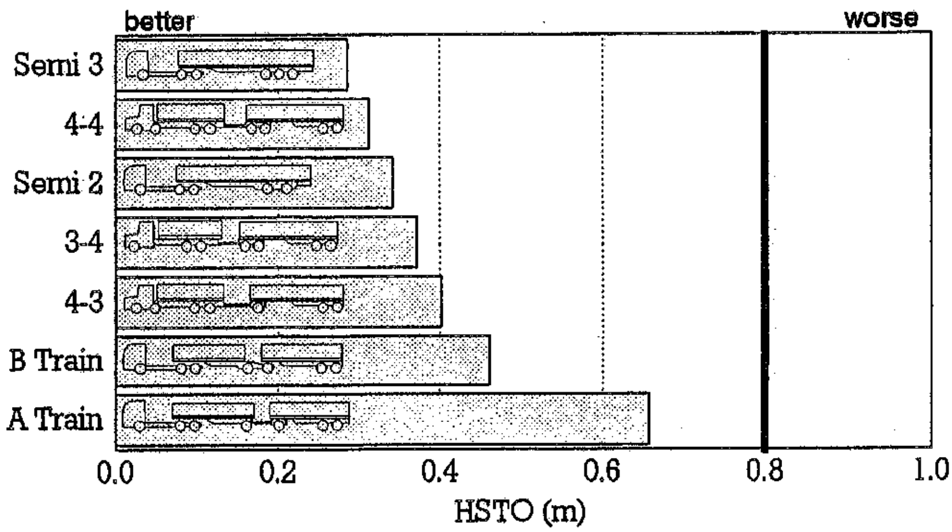

Figure 4
High-Speed Transient Offtracking Results for Typical NZ Vehicles

The High-Speed Transient Offtracking results (Figure 4) are all below the 0.8m target value. The A-train is noticeably worse than the other combinations. Regarding Static Roll Threshold (Figure 5), there is little to distinguish between the different rigs.

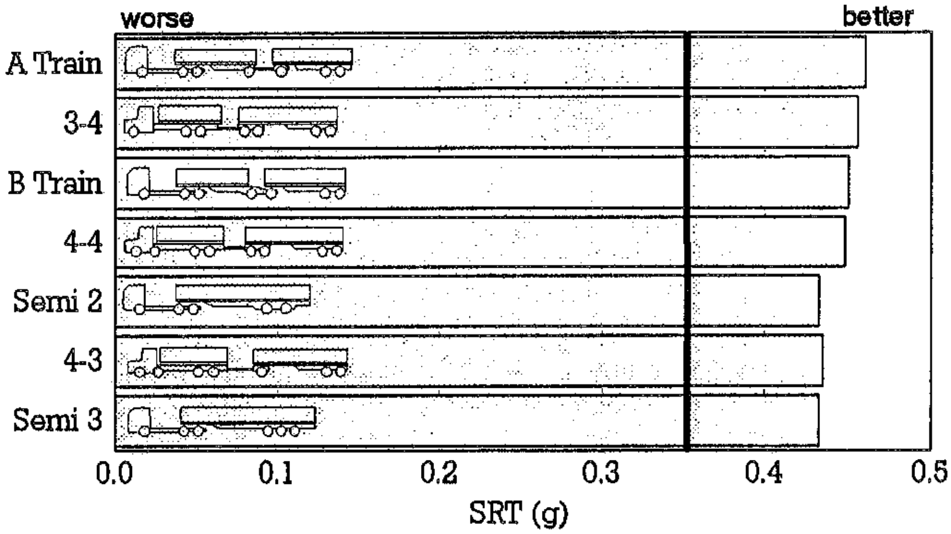

Figure 5
Static Roll Threshold Results for Typical NZ Vehicles

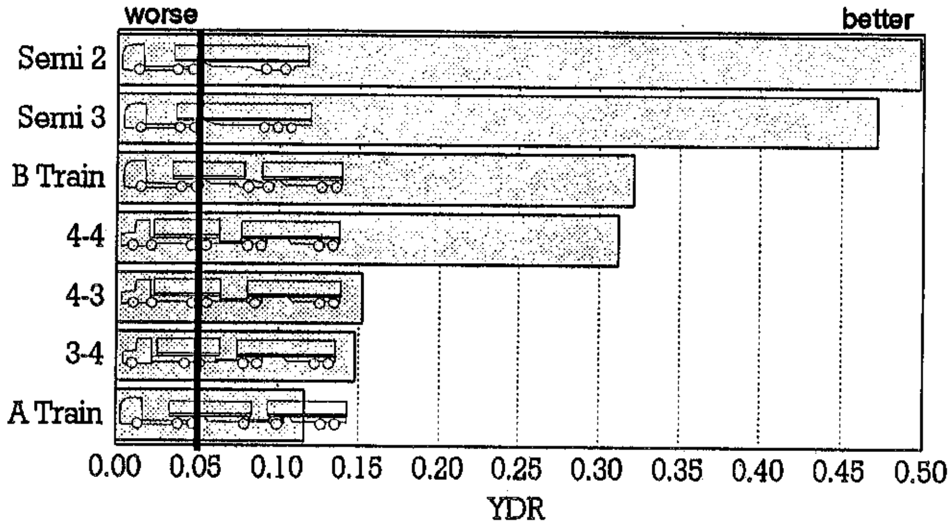

Figure 6
Yaw Damping Ratio Results for Typical NZ Vehicles

Yaw Damping Ratio (see Figure 6 and Appendix B) has quite a range of outcomes. They are all acceptable, though the tractor-semitrailers are significantly superior. It is possible, by bad design or ignorance, to arrive at a vehicle which has a YDR of near zero, which would produce a vehicle whose rearmost trailer would oscillate severely and take a long time for the swaying motion to die out. If that vehicle was driven too fast, it could become completely unstable, swaying back-and-forth until the combination left the road out of control. Yaw Damping Ratio is strongly influenced by forward speed (Figure 7) and rearward loading of the trailer. Thus, while mounting a heavy hoist on the back of a semitrailer should not cause problems, doing the same on dog trailer (without checking the effect on YDR) would be foolish.

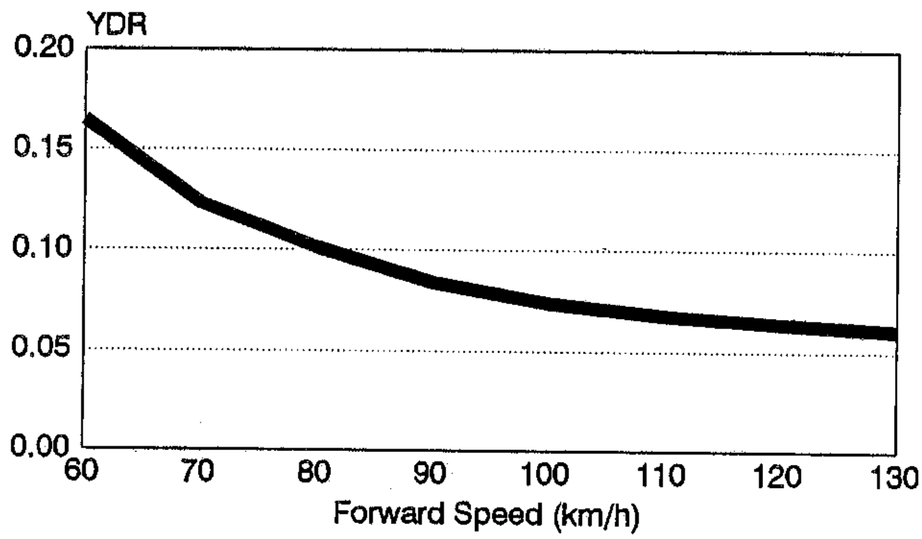

Figure 7
Typical Variation of Yaw Damping Ratio with Forward Speed

High-Speed Steady-State Offtracking (see Figure 8 and Appendix B) is acceptable for all vehicle combinations.

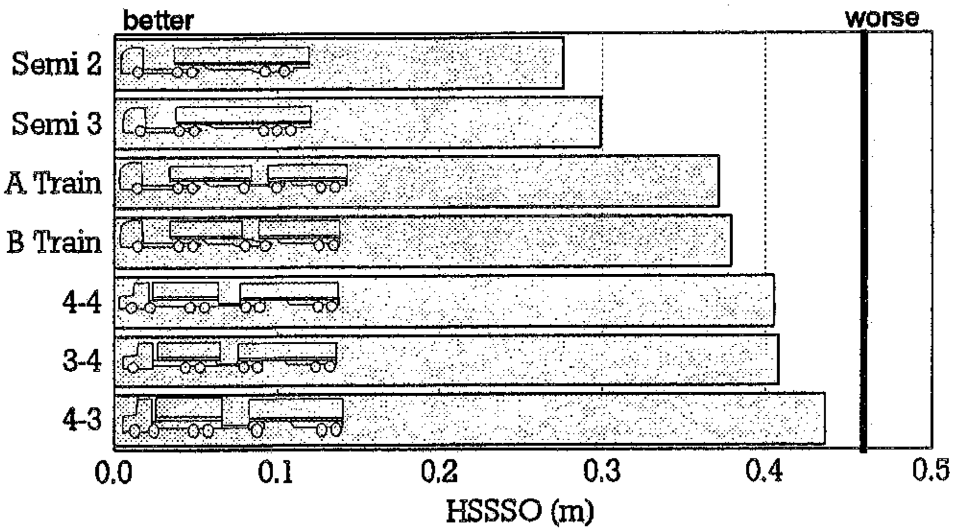

Figure 8
High-Speed Steady-State Offtracking Results for Typical NZ Vehicles

B-trains

The stability advantages of B-trains over A-trains have been well-documented (and summarised in Figure 9). The principal reasons for the stability improvement are the elimination of one articulation point (reducing the rearward amplification) and the roll coupling of the rearmost trailer to the first semi-trailer.

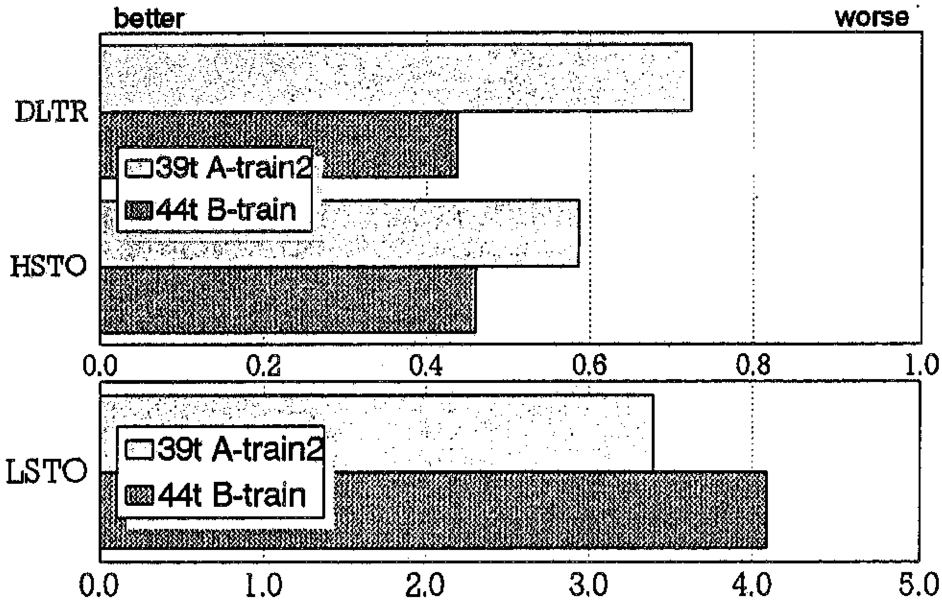

Figure 9
Comparison: A-train and B-train Stability and Manoeuvrability

This improvement comes at the expense of manoeuvrability, however (Figure 2). Besides the direct safety implications of trailers tracking into the paths of other users, the poor manoeuvrability makes B-trains impractical for many operations, reducing the impact of the more stable configuration on overall heavy vehicle safety statistics in NZ.

Better A-trains

A-trains themselves can be improved.

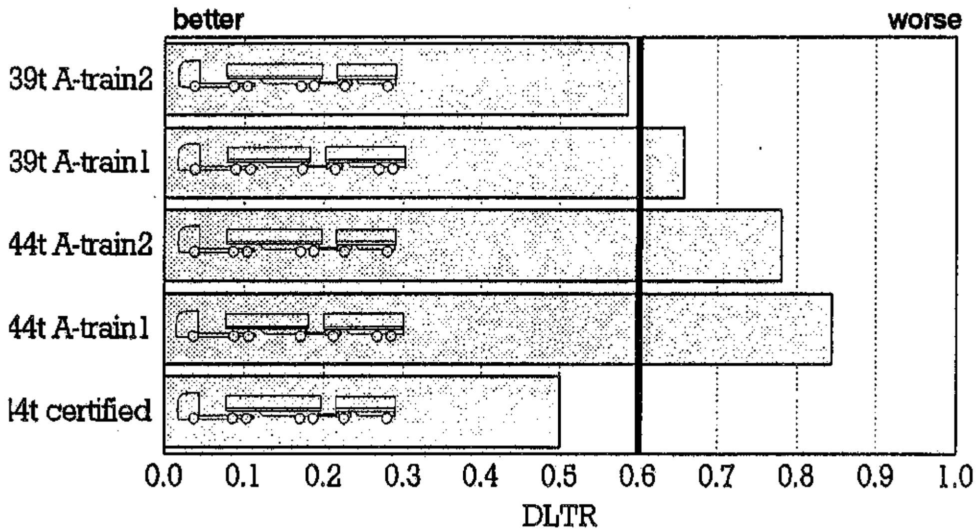

Figure 10
Dynamic Load Transfer Ratio Results for Various A-Trains

Figure 10 indicates the stability of various A-trains at 39 and 44t GCM. It shows that an A-train using a tandem-axle semitrailer and a two-axle dog trailer is significantly better than one with a single-axle semitrailer and a three-axle dog trailer.

Also evident in Figure 10 is the amazing stability performance of purpose-designed 44t A-trains, such as the one illustrated in Figure 11. It illustrates what safety improvements are possible by careful design, even with increased payload.

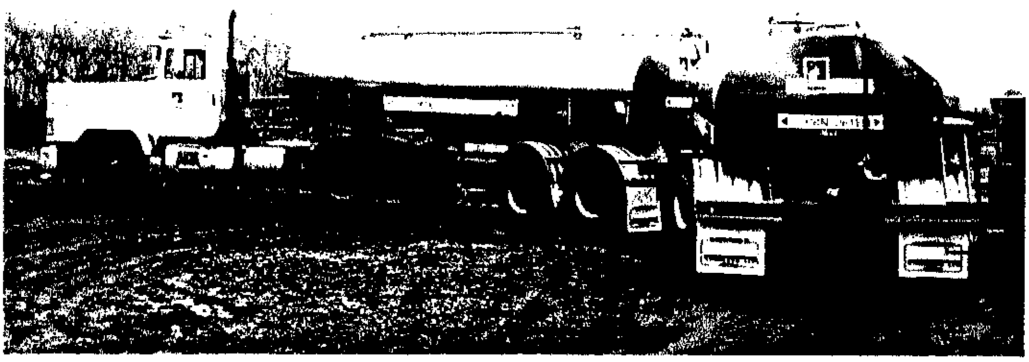

Figure 11
Approved 44 tonne Milk Collection A-Train
(Photo included with permission of Bay Milk Products)

S-trains

One operator devised the trailer configuration: a tractor-semitrailer pulling a pig trailer. He coined it an "S"-train.

"Pig" trailers have one centrally located axle group, and a roll-compliant coupling capable of carrying vertical load. While S-trains do not show stability improvements over A-trains with typical loads, they can also be purpose-designed to advantage, improving both stability and manoeuvrability (Figure 12).

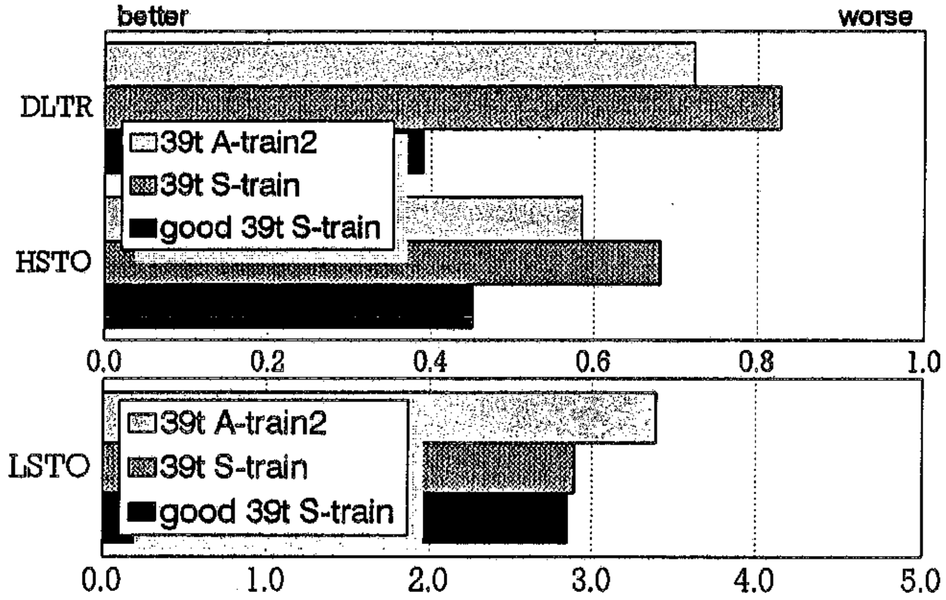

Figure 12
Comparison: A-train and S-train Stability and Manoeuvrability

Modified A-Dollies

There are various means of enhancing A-train stability by modifying the drawbar hitch characteristics. These have been investigated and reported by Chris Winkler of UMTRI[2]. Table C-1 in Appendix C (from Winkler's paper) describes the various designs.

Speed-Sensitive Drawbar

Recent research at DSIR has been oriented to breaking the stability/manoeuvrability compromise.

By installing an additional speed-sensitive link between the semi-trailer and the dolly, it is possible to lock the "ringfeeder" articulation at highway speeds, producing stability approaching B-train levels. At lower speeds (less than 50 km/h) the link can be free to slide, preserving the manoeuvrability of an A-train. Figure 13 illustrates this.

It is intended to develop this concept further.

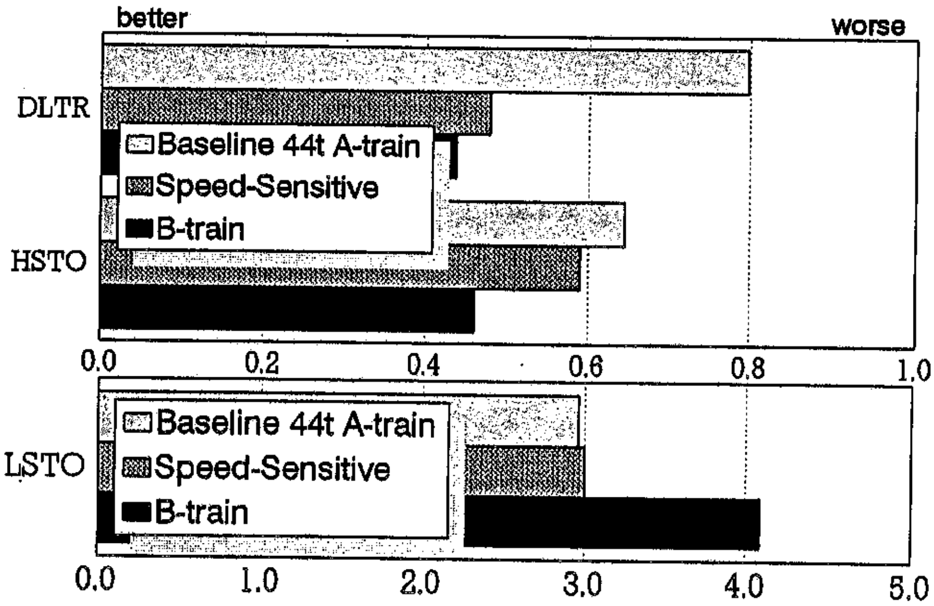

Figure 13
Stability and Manoeuvrability of A-train with Speed-Sensitive Drawbar

Other Configurations

Figure 14 presents the DLTR results for a extended range of NZ vehicles. Several new things should be noted from this.

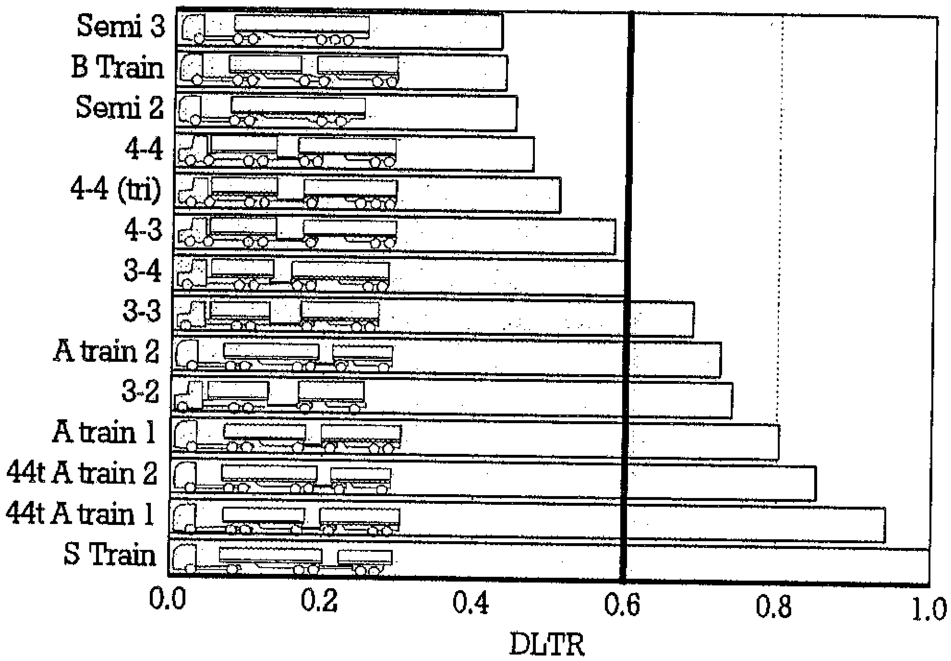

Figure 14
Dynamic Load Transfer Ratio Results for a Large Range of NZ Vehicles

The most significant is the performance of the 3-axle truck with a 2-axle trailer (abbreviated to "3-2") and the 3-axle truck with a 3-axle trailer (or "3-3"). The 3-3 and the 3-2 both do not meet the target value. In fact, the 3-2 is inferior to the better of the two A-trains. Since so much attention has been placed on the stability of A-trains, it would appear that these truck-trailers should also be examined in greater detail. with a view to improving their stability or encouraging alternative configurations.

An extra 8-axle truck trailer is included in Figure 14. It has a 4-axle trailer with three of those axle in the rear group. It clearly performs better than either a 4-3 or 3-4 truck-trailer.

Improving Manoeuvrability of Tractor-Semitrailers

One other approach to improving the safety of modern heavy goods vehicle combinations is to enhance the manoeuvrability of very stable rigs. One of the best overall for stability is the triaxle semitrailer. In its longest legal form it does not negotiate typical urban intersections particularly easily, however. In the past, trailer manufacturers devised self-steering bogies or a self-steering axle mounted some distance behind the tandem axle, in order to provide greater manoeuvrability. Such vehicles were not encouraged in the revised NZ size and weight regulations of 1989.

Using data obtained from NRC, Canada[3] on the physical characteristics of self-steering axles, tractor-semitrailers at 37t and 39t with rear overhangs of 2.5m and 3.2m were simulated to assess the effect of the self-steering axle on stability[4]. FIgure 15 summarises the findings of the investigation. It shows that while low pressures in the self-centring device are undesirable, otherwise the tractor-semitrailer stability is good. Increasing GCM from 37 to 39 tonne and shortening the semitrailer rear overhang were not found to be significant factors. Figure 16 contains stability results and results from some subsequent manoeuvrability analysis to quantify the benefits of the steerable axle. The Ministry of Transport policy on these semitrailers provides for low self-centring pressure at low speed, provided pressure is automatically raised for high-speed operation.

The end result using a speed-sensitive self-steering axle is a very stable triaxle semitrailer, with good manoeuvrability at low speed. This is another good example of "breaking the stability - manoeuvrability compromise".

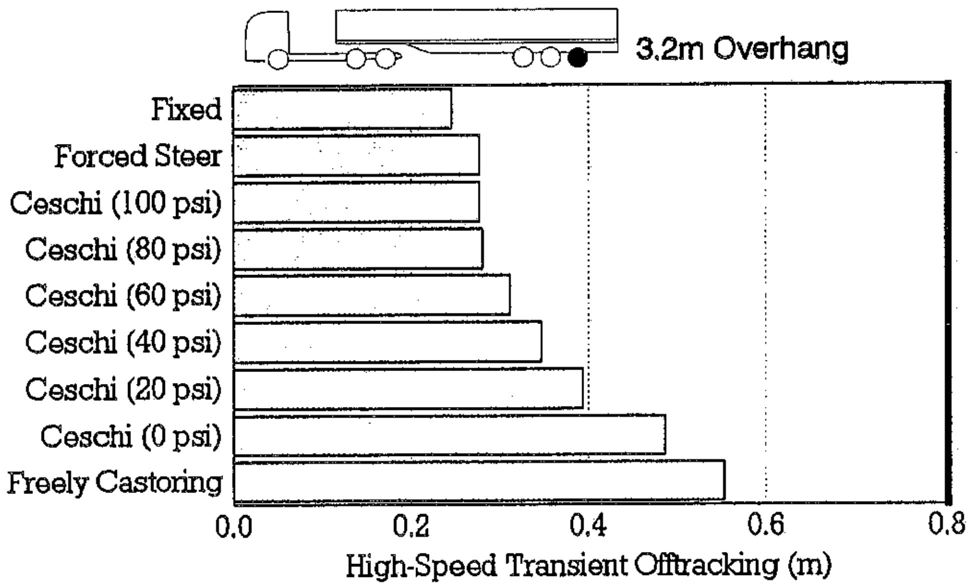

Figure 15
Dynamic Stability of Tractor Semitrailer with
Varying Rearmost Axle Self-Steering Capability

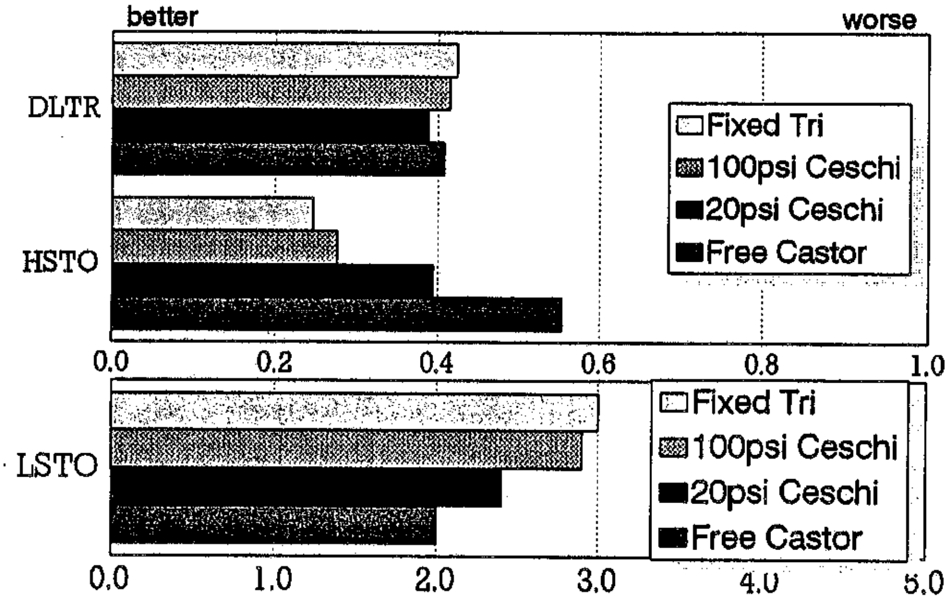

Figure 16
Tractor Semitrailer with Self-Steering Axle: Stability and Manoeuvrability

Conclusions

While, in general, it has been true that stability improvements have been gained at the expense of manoeuvrability, there are a growing number of exceptions. Configurations such as an A-train with a speed-sensitive locking drawbar or tractor-semitrailers with a speed-sensitive self-steer axle are achieving better stability **and** manoeuvrability. Such concepts are likely to be incorporated into the vehicles of the future.

Consider a tractor unit with two or more semitrailers, mounted entirely on "intelligent axles". These axles sense vertical load statically (giving the function of on-board weighing scales built-in) and dynamically (measuring and attenuating the harmful pulsating forces applied to the road, perhaps even adding up the road wear as it happens, to produce a true "User Pays" alternative to Road User Charges). The vertical forces in conjunction with the wheel speed sensor outputs serve to modify the electronic braking signal at the axle, taking into account whole body and inter-axle load transfer. The separate vertical forces for the left and right wheel sets are used directly to determine how near to the rollover threshold the vehicle is operating, and if necessary, a cab-mounted "rollover warning device" is activated. These functions are provided using the axles "built-in" sensors, microprocessor and actuators. An advanced model of the "intelligent axle" even determines wheel slip angles, trailer articulations, lateral accelerations and automatically alters the axle steer angle to optimise the vehicle performance according to the most appropriate criteria: minimising tyre wear, offtracking, trailer snaking, or maximising safety. It would even be possible to critique a driver automatically, coaching them to the best speed, gear ratio, in a given corner, reprimanding when they get inattentive, and even shutting down the engine if their driving gets too dangerous (perhaps impaired by fatigue, drugs or alcohol, or deliberately to thwart a hi-jacker).

Such a vehicle is not inconceivable, given the pressures to increase productivity (such as larger and heavier ISO shipping containers, and loads in general) while maintaining road safety on a constrained roading network, designed for specific vertical axle loadings and cornering capability.

Thus, it is essential that vehicles capable of carting the loads of the future be considered in setting the regulations and standards of today.

Appendix A Comprehensive Vehicle Stability Results

Table A-1 summarises the stability findings for the NZ fleet. Typical vehicle configurations, dimensions and component parameters are used. The load density is assumed to be a uniform 545 kg/m^3, and the centre of gravity height is calculated from the deck area and density.

Table A-1
Stability and Manoeuvrability of NZ Vehicle Combinations

Vehicle	DLTR	HSTO (*m*)	YDR	SRT (*g*)	HSSSO (*m*)	LSTO (*m*)
A-train 1 (39t)	0.80	0.66	0.12	0.46	-0.37	3.23
A-train 2 (39t)	0.72	0.59	0.10	0.49	-0.37	3.39
A-train 1 (44t)	0.94	0.84	0.10	0.40	-0.41	3.22
A-train 2 (44t)	0.85	0.78	0.08	0.43	-0.40	3.38
B-train	0.44	0.46	0.32	0.45	-0.38	4.09
S-train	0.83	0.68	0.10	0.45	NA	2.89
A-train with speed-sensitive drawbar	0.48	0.59	0.14	0.44	0.43	2.96
3-axle truck, 2-axle trailer	0.74	0.48	0.09	0.42	-0.41	2.38
3-axle truck, 3-axle trailer	0.69	0.47	0.12	0.42	-0.44	2.83
3-axle truck, 4-axle trailer	0.60	0.37	0.15	0.46	-0.41	2.69
4-axle truck, 3-axle trailer	0.58	0.40	0.15	0.44	-0.44	3.58
4-axle truck, 4-axle trailer	0.47	0.31	0.31	0.45	-0.41	3.52
4-axle truck, 4-axle trailer (triaxle group)	0.51	0.35	0.16	0.44	-0.42	3.41
Triaxle-semitrailer	0.43	0.29	0.47	0.43	-0.30	3.66
Tandem-axle semitrailer	0.45	0.34	0.50	0.44	-0.28	3.64

Appendix B PERFORMANCE MEASURES, TARGET VALUES AND EVALUATION METHODS

B.1 Static Roll Threshold, Dynamic Load Transfer Ratio & High-Speed Transient Offtracking

These stability parameters are explained in Appendix B of my paper at the previous IRTENZ Seminar[5].

B.2 Yaw Damping Ratio

Yaw Damping Ratio (YDR) is a measure of how rapidly yawing motions are damped out. It is determined by subjecting the truck to a pulse steer input at highway speed (usually 100km/h). Damping ratio is calculated from the ratio of amplitudes of successive oscillations.

The typical vehicle response to this steer input is illustrated in Figure B-1. The rearmost trailer exhibits a classical damped oscillation, with the successive peaks decaying exponentially. (While lateral acceleration has been used here, yaw rate or roll angle could have also been considered.)

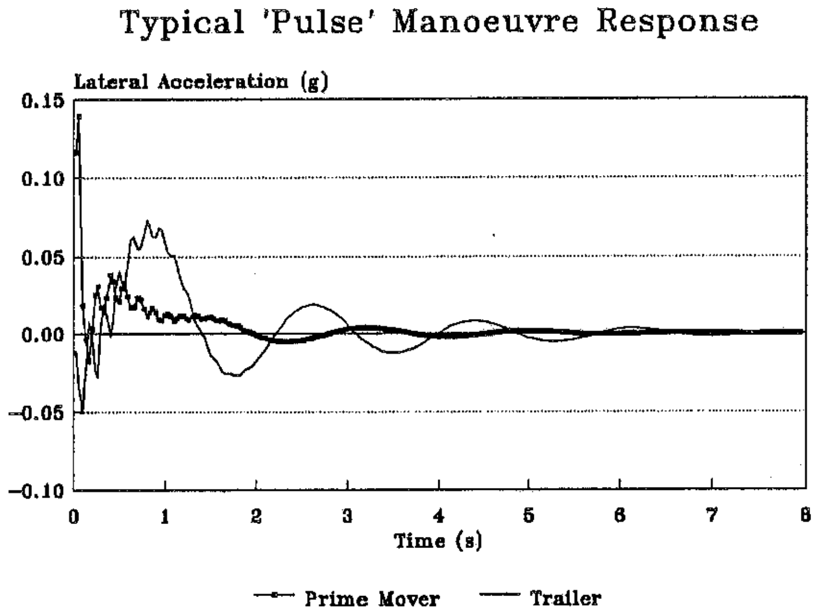

Figure B-1

The first 2 seconds (typically) of the time history record is ignored. This is to ensure the transient effects do not swamp the subsequent steady-state response of the system. The remaining time history record is searched for positive and negative peaks. Logarithmic decrement is first calculated for each of the successive peaks:

$$Log_{DEC} = \ln\left[\frac{AyPk_i}{AyPk_{i-1}}\right] \qquad \text{(B-1)}$$

Then the Yaw Damping Ratio, β, is determined based on the following formula, for each value of Log_{DEC}:

$$Log_{DECi} = \frac{2\pi\beta_i}{\sqrt{\beta_i^2 - 1}} \qquad \text{(B-2)}$$

Expressed in terms of β, this becomes:

$$\beta_i = \frac{-Log_{DECi}}{\sqrt{4\pi^2 + Log_{DECi}^2}} \qquad \text{(B-3)}$$

A target value of 0.15 at 100km/h has been adopted for DSIR stability analysis. This was arrived at from proposed value given by Klein, et al[6] and following communication with Mr C. Winkler of UMTRI.

B.2 High-Speed Steady-State Offtracking

High-Speed Steady-State Offtracking (HSSSO) is a measure of the difference in the paths of the first and last axle groups in a steady high-speed corner. The chosen corner is 393m radius, producing 0.2g lateral acceleration at 100km/h. At that level of lateral acceleration, all the combinations simulated experienced negative offtracking, that is, the rearmost axle group tracked **outside** the steer axle path.

The target value proposed in the Canadian weights and dimensions study was 0.46m. Its significance in NZ is debatable, as we have few long large-radius corners in this country. In North America there are numerous motorway junctions and many of these connect the motorway to another motorway or a similar high-speed route. The merging lane traverses either a 90° or in a clover-leaf junction a 270° curve. A number of single-vehicle rollover incidents on such lanes points to HSSSO as a likely mechanism for trailer tyres to offtrack outboard sufficiently to strike the curb or reach the softer road shoulder, resulting in a trailer rollover. Such corners do not pose a regular hazard in this country.

B.3 Low-Speed Transient Offtracking

Low-Speed Transient Offtracking (LSTO) is a measure of the difference in the paths of the first and last axle groups in a 90° low-speed corner. The standard manoeuvre is a straight lead-in, 11.0m (at the outside tyre track) 90° corner followed by a straight exit, conducted at 8.25km/h.

In the United States and Canada a target value of 6.0m is nominated. This reflects the generous road design approach used in those countries. In New Zealand, the standard adopted for low-speed manoeuvrability appears to be "whatever a B-train can do", since they are the least capable at negotiating intersections, yet are regarded by the MOT as acceptable. In this particular manoeuvre, with the typical B-train layout employed, the LSTO was 4.09m. Thus a suggested target value for NZ vehicles of 4.1m seems reasonable.

Appendix C DESCRIPTIONS OF MODIFIED A-DOLLIES

Modified A-dollies retain the yaw articulation capability between the first trailer and the dolly.

Table C-1
Innovative Dollies and Hitching Hardware

Dolly Type	Description	Inventor, Commercial Interest or Manufacturer
Shifted IC Dollies	Dollies whose hitch hardware causes a shift in the centre of rotation (IC) of the dolly and first trailer away from the hitch point.	
Symmetric Trapezoid hitch	Double drawbars, hinged at both ends, form a symmetric trapezoid about the longitudinal centreline in the plan view with the narrower end forward. The IC is forward of the physical hitch point.	Used by Michelin test fleet. No known active producer.
Asymmetric Trapezoid hitch	Double drawbars, as above except one bar on centreline.	Norman Gallatin. Trapezoid Corp.
Converter, trapezoid hitch	Symmetric trapezoid, converts to rigid connection for low speed manoeuvring.	Marcard Trailer Services
Double-crossed hitch	Double drawbars, hinged at both ends, criss-cross in plan view. The IC is at the cross point, rearward of the physical hitch point.	Arnies Welding. Hamelex Transport.
Roller Cam Hitch	Cam surface of hitch provides forward IC at small articulation angles, rearward IC at large articulation angles.	A.Pavluk, L.Segel, P.Fancher.
Forced Steer Dolly	The wheels of the dolly are forced to steer as a function of ringfeeder articulation angle. Different types are produced with a variety of steering linkages. Used in Europe for "close-coupling".	Royce-Curry, ASTL. Doll "AVL"/ Kogel Kassbohrer. Wackenhut. Ackermann-Fruehauf.
Linked Articulation Dolly	A-dolly with an additional linkage attached directly from trailer to trailer. A fixed relationship between the ringfeeder and turntable articulation angles results.	Truck Safety Systems.
Skid steer dolly	The yaw articulation joint at the turntable is eliminated. That is, the front tyres of the full trailer do not steer at all.	Doetecker Industries.
K-Train	Modification of the skid steer concept. An "auto-steer", self-steering axle is used for the dolly axle, so that the front tyres of the full trailer steer by castor.	Knight Industries.
Roll-stiffened pintle hitch	Fifth wheel-like device is used at the draw bar hitch.	Truck Safety Systems.
Extending Drawbar dollies	The drawbar is caused to lengthen as either ringfeeder articulation or fifth wheel articulation angle increases. For "close-coupling".	Blumhart, Pietz, Meier-Bürstadt. Eck.
Locking A-dolly	Single point drawbar equipped with device which can "lock-out" yaw articulation. Operates as an A-dolly when unlocked and as a B-dolly when locked.	VBG, Sweden.

Source: see paper by Winkler in References

1 Ervin, R. *The Rearward Amplification Respons of Multiply-Articulated Truck Combinations*, 1st IRTENZ Int. Heavy Vehicle Seminar, Rotorua, 1985

2 Winkler, C.B. *Innovative Dollies: Improving the Dynamic Performance of Multi-Trailer Vehicles*, Int. Symp. on Heavy Veh. Weights & Dimensions, Kelowna, Canada, June 1986.

3 Woodrooffe, J.H.F. Personal correspondence, Vehicle Dynamics Lab, National Research Council (NRC), Ottawa, Canada. Some of his self-steering axles data is published in a Roads and Transportation Association of Canada (RTAC) report *Technical Analysis and Recommended Practice for the Double-Drawbar Dolly Using Self-Steering Axles*, J. Woodrooffe, et al.

4 White, D.M. *Stability of Semitrailer with Self-Steering Axle*, DSIR Report 71501587, 1990.

5 White, D.M. *The Dynamic Stability of Various New Zealand Vehicle Configurations*, 3rd IRTENZ Int. Heavy Vehicle Seminar, Christchurch, Aug 1989.

6 *Determination of Trailer Stability Through Simple Analytical Test Methods*, Klein Richard H., Szostak, Henry T. SAE Spec Pub SP-443, p 47-53, 1979