

**STABILITY AND ON-ROAD
PERFORMANCE OF MULTI-
COMBINATION VEHICLES WITH AIR
SUSPENSION SYSTEMS**

STAGE 1 PROJECT

June 2002

**Prepared by Roaduser Systems Pty Ltd
for the Remote Areas Group**

**STABILITY AND ON-ROAD PERFORMANCE OF MULTI-COMBINATION
VEHICLES WITH AIR SUSPENSION SYSTEMS**

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AIR SUSPENSION SYSTEMS**

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GLOSSARY

Lateral acceleration gain	Characteristic of multi-combination yaw-roll mode obtained by plotting the lateral acceleration gain factor (rearmost trailer divided by prime mover) against the steering input frequency
Oversteer	Prime mover handling characteristic measured by sensitivity of the yaw response to steering input, and its dependence on lateral acceleration; sensitivity of oversteering vehicle increases with lateral acceleration
Rearward amplification	Ratio of peak lateral acceleration of rear trailer to that of prime mover in a standard lane-change manoeuvre
Roll centre height (suspension)	Height above ground of suspension roll centre
Roll steer coefficient (suspension)	Measure of amount of axle steer angle generated per unit suspension roll angle
Roll stiffness (suspension)	Measure of amount of roll permitted by the suspension (between axle and body) per unit overturning moment
Trailing fidelity (rear movement)	Performance characteristic of multi-combination yaw-roll behaviour obtained by measuring the 95 th%ile lateral displacement of the rear trailer under straight-line travel on a level, moderately rough road surface
Understeer	Prime mover handling characteristic measured by sensitivity of the yaw response to steering input, and its dependence on lateral acceleration; sensitivity of understeering vehicle decreases with lateral acceleration
Yaw damping	Performance characteristic of multi-combination yaw-roll mode obtained by measuring the rate of decay of rear trailer yaw oscillations following a pulse steer input
Yaw motion	Angular motion of prime mover, trailer or dolly measured about a vertical axis

SUMMARY

Objectives

Roaduser Systems Pty Ltd was commissioned by Transport WA, with the assistance of the National Road Transport Commission (NRTC), to investigate further the on-road performance of heavy vehicles incorporating air suspension systems and in particular, multi-combination vehicles, with the ultimate aim of improving vehicle handling, stability and consequently, road safety. This work represents Task 1 of the Remote Areas Group (RAG) initiative “Stability and On-Road Performance of Multi-Combination Vehicles With Air Suspension Systems”. One of the goals of these projects is to resolve any likely deficiencies in vehicle performance caused by the use of air suspension systems. It is not the goal to prohibit the use of air suspensions on road train combinations.

Background

An increasing focus on the use of air suspension systems on heavy combination vehicles has occurred due to the implementation of higher mass limits under the national mass limits review conducted by the NRTC. While this is a desirable outcome for productivity reasons and infrastructure, further work to provide guidance to operators and manufacturers in the best use and application of air suspension systems for various multi-combination vehicle configurations is considered necessary.

The primary areas of concern relate to multi-combination vehicles with air suspension systems that typically operate at high mass limits with high centre of gravity loads. There is strong anecdotal evidence that air suspension modifications on some vehicles are being undertaken to counteract some of the reported undesirable behaviour .

Reported undesirable behaviour includes increased roll, sway and lurch of the vehicle making it difficult for the driver to control the combination. Drivers also reported that air sprung prime movers had a tendency to follow road indentations requiring a greater steering effort to keep the vehicle on its intended path. Air suspended dollies were reported to increase roll, reduce stability and behave erratically under heavy braking.

Scope and Content

Task 1 was an investigation of double and triple road train combinations utilising various suspension types to establish their performance characteristics and performance limits with particular reference to the effect of vehicle centre of gravity height, speed, road roughness and product carried.

A range of combinations of suspension types (air and mechanical) was examined, including:

- Vehicles or combinations of vehicles using air suspensions only (except steer axle)
- Vehicles or combinations of vehicles using air suspensions in combination with mechanical suspensions
- Vehicles or combinations of vehicles using mechanical suspensions only.

The project also considered that:

- Many of these vehicles are operated at higher mass limits to take advantage of the national higher mass limits available with road-friendly suspensions, and the additional extra mass limits allowed by WA and the NT under their respective concessional loading schemes
- A large number of these vehicles operate on outback roads which can have a effect on vehicle dynamics and vehicle maintenance requirements, including damage and wear of dampers which can, in turn, significantly effect the characteristics of the suspension system.

The work undertaken included:

- Literature review
- Investigation of multi-combination vehicles that were reported to be problematic in terms of increased yaw and roll response, vehicle handling and trailing fidelity.
- Consideration of the effects of any major modifications made to these heavy vehicle combinations.
- Computer simulation of the multi-combination vehicles; existing simulation models were significantly enhanced to consider specific issues raised by road train operators and to evaluate performance under more realistic road train operating conditions
- Recommendations for any further work required, including instrumented field testing of multi-combination heavy vehicles.

Management and Consultation

The Task1 Project was managed by John Dombrose (Transport Western Australia) with the assistance of Barry Hendry (NRTC) and John Hollins (DTW NT) who formed the project management team. They were assisted by a Project Management Team Advisory Committee representing truck manufacturers, suspension manufacturers, equipment manufacturers, remote area operators, agencies, the Truck Industry Council and the Australian Trucking Association.

The work was carried out in consultation with the Remote Areas Group of the Remote Areas Ministerial Council.

Research Findings

The study has indicated some major deficiencies in the performance of the largest, heaviest road trains when simulated with suspension properties similar to current air suspensions used on dollies, trailer axles and drive axles. These performance deficiencies have similarities to the problems described by road train operators.

The study has also indicated some means of avoiding these deficiencies and some of these means appear to concur with certain actions already taken by some road train operators.

Problems Reported

Poor dynamic tracking behaviour - variously described as poor tracking, poor dynamics, swaying, wagging, wandering, leaning, erratic tracking, hanging down and poor feel – was the main problem reported by a number of operators. A related persistent complaint was

that it was necessary to reduce speed to overcome the problems of poor dynamics. A further significant complaint was shock absorber performance.

Some operators complain of dangerous behaviour on the road and report accidents which have been caused by poor dynamics. Reported dangerous behaviour includes excessive roll and excessive swaying of trailers.

Some operators also complain of difficulties in learning to drive combinations safely and the dangers of using drivers who are unfamiliar with the vehicles in question.

Interventions by Operators

Most of the modifications undertaken by operators were applied to air suspensions. These modifications covered both the prime mover and the trailers and included larger air lines, ride height control valve conversions and shock absorber changes.

Operators have also been forced to make significant attempts to overcome problems with air-suspended dollies. One operator installed an additional ride height control valve on a tandem air dolly so that each axle was controlled independently; this was reported to fix the problem. Another operator reported that it was difficult to fix air-suspended dollies, and another reported that he had converted back from air to mechanically-suspended dollies.

One livestock operator converted four sets of road train trailers from air to mechanical suspension and fixed the problems he was experiencing. The combinations continued to operate at the same weights, due to volumetric loading.

Types of Road Trains Involved

Virtually all of the problem combinations were triples, comprising tandem drive prime mover, triaxle trailers and tandem dollies.

All of the vehicles investigated had air suspensions fitted to the trailers. Most of the prime movers (but not all) had air suspension. Some of the dollies had air suspension.

Some operators have tried converting back from air to mechanical suspension; this only occurred on trailers and dollies. None of the prime movers were converted to mechanical suspension.

Trailers involved included::

- Livestock (which combines high mass under volumetric loading, high COG and generally shorter wheelbase) – by far the majority of problem vehicles
- Tipper (which generally has shorter wheelbase)
- Flat-top
- General freight
- Tanker, dry bulk tanker and container.

Most of the dollies involved were air-suspended, and - in terms of problem combinations – the vast majority were air-suspended. As there appeared to be relatively few air-suspended dollies in road train service, air-suspended dollies appeared to be a significant factor in problem combinations.

Key Dynamic Performance Issues

While the report contains a wide range of performance measures, based on the current Austroads/NRTC Performance Based Standards (PBS) Project (which has not been finalised) and on other studies in the literature, road trains are specialised and complex vehicle configurations and require careful evaluation. It is particularly important to listen to the comments of drivers and operators and to fully consider the role of the driver.

Performance measures also need to be distinguished in that they may relate to the dynamics of the entire combination, or could mainly address the controllability of the prime mover.

The three most relevant “combination” performance measures for this study were found to be:

- Lateral acceleration gain (frequency sweep) – this locates the peak gain and the frequency at which it occurs; it also provides the gain at normal steering frequency; this information speaks to the degree of exaggerated response at the rear of the combination to steering input of a particular magnitude and frequency content – in particular, it quantifies the unwanted exaggerated trailer response at normal steering frequencies which the driver cannot avoid
- Yaw damping – this speaks to the persistence of trailer yaw motions once they are created and becomes critically low (poor performance) for some road trains and road train variables
- Trailing fidelity (95 th%ile movement) – this speaks to the amount of lateral movement at the rear of the combination when the driver is trying to steer a straight line on a moderately rough road.

One “prime mover” performance measure was also found to be important: the handling diagram, and in particular the lateral acceleration at which the transition from understeer to oversteer may occur (see “second point” in Figure 1).

Yaw-Roll Mode of Triple Road Train

Most of the swaying problems reported by triple road train operators are caused by the yaw-roll dynamic mode of the combination.

The yaw-roll dynamic mode of a triple road train has a very low natural frequency, a low damping ratio and a high gain. Each trailer sways and rolls more than the trailer in front of it. Because the sway increases from each trailer to the next, the lateral acceleration increases and this causes the roll to increase. When the roll increases, tyre vertical loads increase and the tyre side force capacity reduces. This causes the trailer to sway more to develop the required side force. If the suspension allows more roll to occur (low roll stiffness) or geometrically reduces the tyre side force (roll steer), this closed loop of effects is accentuated.

Crucially, the frequency of the roll mode is reduced by higher mass, increased COG height and lower roll stiffness. The frequency of the combined yaw-roll mode is well above the normal steering frequency for most heavy vehicles, but can be reduced sufficiently in triple road trains so that normal steering input produces an abnormally high output (swaying).

The frequency sweep measures, relating lateral acceleration at the rear trailer to that of the prime mover, showed the following critical features:

- The peak gain of the triple is more than twice that of the double; the dominant frequency is not significantly different between triple and double
- The dominant frequency is strongly affected by COG height and mass (0.3 - 0.4 Hz for the stock vehicle with high mass and COG versus 0.5 Hz for the tanker); the fact that the gain is highly sensitive to frequency means that the high COG and mass road train will have much higher rearward amplification at normal steering frequencies (around 0.25 Hz)
- Suspension type (generic air versus generic mechanical) affects the dominant frequency; generic air suspension on the trailers reduces the dominant frequency by up to 0.1 Hz (or approximately 20 %)
- At normal steering frequencies (0.25 Hz): triples have gains generally more than twice those of doubles, high COG and mass produce more than double the gain and air suspension on trailers approximately doubles the gain for high COG and mass only; the net effect on triples is that air suspension combined with high COG/mass produces three times the gain at normal steering frequencies.

The ability of the combination to damp out trailer oscillations after they have occurred is quantified in the yaw damping measure. The study found that:

- Yaw damping of the triple higher mass and COG (stock) is *only one third* that of the corresponding double
- Higher mass and COG (stock) in triples produces yaw damping below the minimum recommended PBS value of 15 %
- With high mass and COG, generic air suspension produces less than half the damping of the generic mechanical suspension.

Rear movement (trailing fidelity) of the triple on a road of moderate roughness increases by approximately 50 % with higher mass and COG (as for a stock vehicle) and by almost 40 % for generic air suspensions versus generic mechanical suspension.

Handling of Road Train Prime Mover

The handling of the prime mover is affected by the mass and COG height of the lead trailer and, to a limited extent, by the suspension. The strongest effect is mass and COG height: for the higher mass and COG height case, the transition from understeer to oversteer occurs at a lateral acceleration of 0.18 - 0.22 g, compared to 0.25 – 0.30 g for the tankers. Regardless of the generic suspension type, the higher mass and COG height produces oversteering at a relatively low lateral acceleration.

Mass and COG height have been found to be major factors in all four key performance measures; of these, mass is the stronger influence.

Key Influencing Factors

Suspension parameters also play a major role in the three combination vehicle measures, and to a lesser extent in prime mover handling. Roll stiffness is the most influential suspension parameter, strongly affecting combination rear response, damping and movement. Roll centre height is also a critical parameter. Roll steer coefficient has a

major effect on rear movement. The load distribution within axle groups has an appreciable but generally small effect.

Dollies play a critical role in the dynamic performance of triples and the crucial parameters are: roll stiffness, roll centre height and load distribution (where a forward weight bias degrades performance).

Performance Deficiencies Indicated

The rear trailer motion characteristics of triple road trains with high mass and COG height (as for stock vehicles) and air suspension (similar to the generic parameters used) appear to be undesirable in that:

- The natural yaw frequency of the combination is close to normal steering frequency, causing highly exaggerated steering response at the rear of the combination
- The damping of the trailer oscillations created is insufficient
- The rear movement, as affected by road roughness, is also exaggerated.

The handling of prime movers with low-roll-stiffness, high-roll-steer air suspension becomes undesirable when connected to trailers with high mass and COG height.

Air-suspended dollies with low roll stiffness and low roll centre height cause triple road train combinations with high mass and COG height (as for stock vehicles) to have undesirable rear trailer motion characteristics.

Deficiencies related to undesirable rear trailer motion characteristics are speed-sensitive and the yaw damping in particular decreases with speed.

Task 1 Recommendations

The apparent performance deficiencies of multi-combination vehicles identified in this study are potentially serious and justify:

- Further investigation to confirm the study findings, especially in relation to the fact that the current findings are based on computer simulation
- If required, development of means to improve multi-combination vehicle handling.

Confirmation of Performance Deficiencies

It is recommended that field testing of appropriate multi-combination vehicles is carried out to confirm the key results of this study. Testing should encompass multi-combinations the handling of which owners and drivers are not satisfied with, as well as multi-combinations with apparently satisfactory handling. Test methods should be suitable for quantifying two basic types of performance deficiency: (i) high-gain, low-frequency yaw-roll dynamics and (ii) tendency to prime mover oversteering. The test plan should also include assessment of the effectiveness of feasible countermeasures for multi-combinations with performance deficiencies and should allow for further validation of the simulation models used in this study.

Test vehicles should concentrate on triple road train configurations. At least one such vehicle with yaw-roll dynamics problems should be tested, and at least one vehicle with oversteering tendency. Testing should include one triple stock road train with air suspension and a similar road train with mechanical suspension, both tested at the same concessional weights.

On-road test methods should be capable of measuring:

- Lateral acceleration gain through the frequency range 0 – 2 Hz
- Yaw damping
- Roll angles and roll gradients of least favoured suspensions (those on the rear trailer and prime mover).

In addition, the following measurements need to be made:

- Quasi-static load sharing and load skew coefficients of least favoured suspensions
- Roll stiffness, roll centre height and roll steer coefficient of suspension types used.

Improvement to Multi-Combination Vehicle Handling

If comparative testing following the above principles confirms problems with (i) the low-frequency yaw-roll mode and/or (ii) prime mover handling, further testing should be carried out to determine the effectiveness of known countermeasures and to provide a basis for guidelines for road train dynamic improvement and for any new vehicle or component performance standards which may be required for road trains. According to the simulations carried out, certain dolly and suspension controls could avoid the high mass/COG triple performance deficiencies indicated in this study and allow the continued use of (complying) air suspension.

Based on the indications of the present study, the following countermeasures may be relevant for problem multi-combinations:

- Dollies with sufficient roll stiffness and roll centre height as well as low load skew coefficient
- Sufficient roll stiffness and roll centre height on trailer suspensions
- Sufficient roll stiffness and roll centre height on prime mover suspensions and sufficiently low roll steer coefficient

and these countermeasures should be considered in the testing, along with any other countermeasures which appear to address the road train dynamics issues identified in Task 1.

CONTENTS

Management and Consultation	3
Research Findings	3
1. INTRODUCTION	1
1.1 Background.....	1
1.2 Stage 1 Task.....	2
1.2.1 Objective	2
1.2.2 Scope and content.....	2
1.2.3 Management and Consultation	3
2. LITERATURE REVIEW	4
2.1 Operational Stability and Performance of Air Suspensions on Various Vehicle Configurations. (Estill & Associates P/L, September 2000). (1).....	5
2.2 Investigation into the Specification of Heavy Trucks and Consequent Effects on Truck Dynamics and Drivers: Final Report. Report prepared for DoTRS by Roaduser International P/L (2)	8
2.2.1 Vehicle handling quality.....	9
2.2.2 Prime Mover Response to Steering	9
2.2.3 Prime Mover Response to Disturbances	11
2.2.4 Suspension Roll Stiffness.....	11
2.2.5 Suspension Roll Steer.....	11
2.2.6 Tendency to Roll Over.....	12
2.2.7 Bump Steer	14
2.2.8 On-centre Steering Variability	15
2.2.9 Air suspension Pressure Differential.....	15
2.2.10 Measurement of Performance	15
2.3 Manufacturer's Guidelines on Application of Air Suspensions.	16
2.4 An Operational Field Test of Long Combination Vehicles Using ABS and C-Dollies. The University of Michigan Final Technical Report UMTRI-95-45-1. (1995) (4)	18
2.5 On Road Dynamic Performance Testing of MAD and MAP Vehicle Combinations (Roaduser Systems 2001) (3)	19
2.6 ARTSA Air Suspension Code - Guideline for Maintaining and Servicing Air Suspensions for Heavy Vehicles, May 2001	23
2.7 Stability Of Heavy Vehicles With Increased Mass Limits For Dual-Tyred Single Axles and Road-Friendly Suspension, NRTC report prepared by Roaduser International, March 1999.....	23
2.8 Draft NRTC Report on Non-Air Road Friendly Suspension	24
2.9 Definition of Potential Performance Measures and Initial Standards, NRTC April 2001	24
2.10 Organisation for Economic Co-operation and Development (OECD) Technical Report on Dynamic Interaction between Vehicles and Infrastructure Experiment (DIVINE), 1998.....	25
2.11 Handbook of Vehicle – Road Interaction, David Cebon, 1999.	25
3. DISCUSSION OF LITERATURE.....	27
3.1 Handling	27
3.2 Roll Stiffness and Roll Steer.....	27
3.3 Measurement of Performance	27
3.4 Suitability of Air Suspension	28
3.5 Mechanisms for Investigation.....	29
3.6 Performance Based Standards	29

4.	PROBLEM VEHICLES AND MODIFICATIONS	30
4.1	Problems Reported	30
4.2	Solutions Implemented by the Road Train Industry	31
4.3	Characteristics of Vehicles Investigated.....	31
4.3.1	<i>Trailer characteristics</i>	32
4.3.2	<i>Prime mover characteristics</i>	32
4.3.3	<i>Dolly characteristics</i>	32
4.4	Relevance of Performance Measures	33
4.4.1	<i>Relevant PBS measures</i>	33
4.4.2	<i>Additional measures</i>	34
4.5	Additional Vehicle Parameters	35
5.	COMPUTER SIMULATION OF MULTI-COMBINATION VEHICLES.....	37
5.1	Baseline Performance Measures.....	40
5.2	Initial Investigation of Real-World Road Train Variables	43
5.3	Key Results from Baseline Simulations	44
5.3.1	<i>Effects of generic variables</i>	44
5.3.2	<i>Effects of Real-World Road Train Variables</i>	45
5.3.3	<i>Most relevant performance measures</i>	45
5.3.4	<i>Effects of key road train variables</i>	46
5.4	Indicators for Performance Deficiencies with Air Suspension.....	50
5.4.1	<i>Deficient yaw dynamics</i>	50
5.4.2	<i>Handling problems</i>	50
5.5	Indicators for Resolving Performance Deficiencies with Air Suspension	54
5.5.1	<i>Deficient yaw dynamics</i>	54
5.5.2	<i>Prime mover handling problems</i>	60
5.6	Operational Influences.....	61
6.	MAIN FINDINGS & CONCLUSIONS.....	63
6.1	Main Issues Identified by Operators and Drivers	63
6.1.1	<i>Problems encountered</i>	63
6.1.2	<i>Interventions by operators</i>	64
6.1.3	<i>Types of road train involved</i>	64
6.2	Most Relevant Performance Measures	64
6.3	Dynamic Performance of Road Train Triples	65
6.4	Performance Deficiencies Indicated.....	67
6.5	Further Investigation and Improvement of Multi-Combination Handling	67
7.	REFERENCES	69

LIST OF FIGURES

Figure 1	Handling Diagram (12).....	10
Figure 2	Roll Steer Definition	12
Figure 3	Vehicle Parameters that influence vehicle roll stability	13
Figure 4	Ideal motions of the drag link during suspension articulation.....	14
Figure 5	Typical C-dolly (US and Canada)	18
Figure 6	MAD and MAP Test Vehicles.....	20
Figure 6	(cont) MAD and MAP Test Vehicles	21
Figure 7	Baseline double road train combinations	38
Figure 8	Baseline triple road train combinations.....	39
Figure 9	Lateral acceleration gain vs frequency for baseline triple stock road trains.....	42
Figure 10	3-Point handling performance diagram for triple stock crates with best and worst case drive axle group suspensions	51
Figure 11	Lateral acceleration gain vs frequency for triple stock road train stock crates with air suspension parameter variations	53

LIST OF TABLES

TABLE 1.	MAD AND MAP VEHICLE SPECIFICATIONS.....	19
TABLE 2.	RELEVANCE OF PERFORMANCE BASED STANDARD MEASURES	25
TABLE 3.	POTENTIAL MEASURES – PBS PROJECT.....	34
TABLE 4.	MASS AND COG PARAMETERS IN INITIAL SIMULATIONS.....	47
TABLE 5.	SUSPENSION PARAMETERS IN INITIAL SIMULATIONS.....	48
TABLE 6.	SUSPENSION PARAMETERS FOR FURTHER HANDLING SIMULATIONS (STOCK TRIPLE)	51
TABLE 7.	PARAMETERS FOR FURTHER BUMP STEER SIMULATIONS (STOCK TRIPLE)	52
TABLE 8.	SUSPENSION PARAMETERS FOR FURTHER YAW DYNAMICS SIMULATIONS (STOCK TRIPLE).....	55
TABLE 9.	DOLLY PARAMETERS FOR FURTHER YAW DYNAMICS SIMULATIONS (STOCK TRIPLE).....	57
TABLE 10.	ADDITIONAL SIMULATIONS FOR DOLLY SUSPENSION ROLL CENTRE HEIGHT (STOCK TRIPLE)	59
TABLE 11.	DRIVE AXLE AIR SUSPENSION PARAMETERS (STOCK TRIPLE).....	60
TABLE 12.	EXTENDED BASELINES (TRIPLES) AT EXPANDED SPEED RANGE (UP TO 100 KM/H).....	61
TABLE 13.	WORST CASE VARIABLES (STOCK TRIPLES) AT EXPANDED SPEED RANGE (100 KM/H).....	62

1. INTRODUCTION

The role of the Remote Areas Group (RAG) is to act as the peak advisory body to the Remote Area Ministerial Council (RAMC), and in addition provide advice to organisations such as the National Road Transport Commission (NRTC) and individual jurisdictions on issues and reforms affecting remote areas. In its broader role RAG may also resolve and implement solutions where there is consensus amongst its members and agreement from the RAMC.

This project is based on the Terms of Reference (TOR) 'Stability and On-Road Performance of Multi-Combination Vehicles With Air Suspension Systems' agreed to at the Dubbo meeting of RAG which was held on the 19th February 2001.

The TOR provides for three stages of investigation. The three stages of investigation will be collectively referred to as the Principle Project whilst the sub projects will be referenced according to their respective stage numbers. This project will therefore be known as the Stage 1 Project and referred to in this manner throughout this document.

1.1 Background

An increasing focus on the use of air suspension systems on heavy combination vehicles has occurred due to the implementation of higher mass limits under the national mass limits review conducted by the NRTC during 1993-1996¹. While this is a desirable outcome for productivity reasons and infrastructure, further work to provide guidance to operators and manufacturers in the best use and application of air suspension systems for various multi-combination vehicle configurations is considered necessary.

The primary areas of concern relate to multi-combination vehicles with air suspension systems that typically operate at high mass limits with high centre of gravity loads. There is strong anecdotal evidence that air suspension modifications on some vehicles are being undertaken to counteract some of the reported undesirable behaviour .

Reported undesirable behaviour includes increased roll, sway and lurch of the vehicle making it difficult for the driver to control the combination. Drivers also reported that air sprung prime movers had a tendency to follow road indentations requiring a greater steering effort to keep the vehicle on its intended path. Air suspended dollies were reported to increase roll, reduce stability and behave erratically under heavy braking.

As a result, drivers reported a preference for spring dollies that they felt were safer and considered their use resulted in a combination that was much easier to control.

The survey conducted by Estill & Associates (1), provided sufficient anecdotal evidence to make it apparent that guidelines for the use of air suspension systems in multi combination vehicles would be a positive safety initiative and of assistance to both manufacturers and operators alike.

One of the goals of the projects is to resolve any likely deficiencies in vehicle performance caused by the use of air suspension systems. It is not the goal to prohibit the use of air suspensions on road train combinations.

¹ The higher mass limits agreed in principle by Ministers in April 1998 required road-friendly suspensions certified to Vehicle Standards Bulletin (VSB) 11

1.2 Stage 1 Task

1.2.1 Objective

To investigate further the on-road performance of heavy vehicles incorporating air suspension systems and in particular, multi-combination vehicles, with the ultimate aim of improving vehicle handling, stability and consequently, road safety.

1.2.2 Scope and content

The Stage 1 Project was an investigation of double and triple road train combinations utilising various suspension types to establish their performance characteristics and performance limits with particular reference to the effect of vehicle centre of gravity height, speed, road roughness and product carried.

A range of combinations of suspension types (air and mechanical) was examined, including:

- Vehicles or combinations of vehicles using air suspensions only (except steer axle)
- Vehicles or combinations of vehicles using air suspensions in combination with mechanical suspensions
- Vehicles or combinations of vehicles using mechanical suspensions only.

The project also considered that:

- Many of these vehicles are operated at higher mass limits to take advantage of the national higher mass limits available with road-friendly suspensions, and the additional extra mass limits allowed by WA and the NT under their respective concessional loading schemes
- A large number of these vehicles operate on outback roads which can have an effect on vehicle dynamics and vehicle maintenance requirements, including damage and wear of dampers which can, in turn, significantly effect the characteristics of the suspension system.

The tasks undertaken as part of this study were:

- Task 1 - Literature Review
- Task 2 - Investigation of multi-combination vehicles that were reported to be problematic in terms of increased yaw and roll response, vehicle handling and trailing fidelity.
- Task 3 – Consideration of the effects of any major modifications made to these heavy vehicle combinations.
- Task 4 - Computer simulation of the multi-combination vehicles
- Task 5 - Recommendations for any further work required, including instrumented field testing of multi-combination heavy vehicles
- Task 6 – Reporting.

1.2.3 Management and Consultation

The Task1 Project was managed by John Dombrose (Transport Western Australia) and Barry Hendry (National Road Transport Commission) with the assistance of a Project Management Team Advisory Committee representing truck manufacturers, suspension manufacturers, equipment manufacturers, remote area operators, agencies, the Truck Industry Council and the Australian Trucking Association.

The work was carried out in consultation with the Remote Areas Group of the Remote Areas Ministerial Council.

2. LITERATURE REVIEW

A literature review of the following reports/texts/guides was undertaken:

- Operational Stability and Performance of Air Suspensions on Various Vehicle Configurations. (Estill & Associates P/L, September 2000) (1)
- Investigation into the Specification of Heavy Trucks and Consequent Effects on Truck Dynamics and Drivers: Final Report. (Report prepared for DoTRS by Roaduser International P/L) (2)
- Manufacturer's Guidelines on Application of Air Suspensions.
- On Road Dynamic Performance Testing of MAD and MAP Vehicle Combinations (Roaduser Systems 2001) (3)
- An Operational Field Test of Long Combination Vehicles Using ABS and C-Dollies. (The University of Michigan Final Technical Report UMTRI-95-45-1 1995) (4)
- ARTSA Air Suspension Code - Guideline for Maintaining and Servicing Air Suspensions for Heavy Vehicles, May 2001 (5)
- Stability Of Heavy Vehicles With Increased Mass Limits For Dual-Tyred Single Axles and Road-Friendly Suspension (NRTC report prepared by Roaduser International, March 1999) (6)
- Draft NRTC report on Non-Air Road Friendly Suspension (7)
- Definition of Potential Performance Measures and Initial Standards (NRTC April 2001) (8)
- Organisation for Economic Co-operation and Development (OECD) Technical Report on Dynamic Interaction between Vehicles and Infrastructure Experiment (DIVINE), 1998 (9)
- Handbook of Vehicle – Road Interaction (David Cebon, 1999) (10)

The literature review concentrated on suspension characterisation and effects on vehicle performance, particularly multi-combination vehicles; this included any material regarding comparisons between air and mechanical suspension performance, any operational deficiencies of air suspension systems or effects if they are used beyond their intended purpose. The review also considered the relevance of performance-based standards (PBS) in assessing dynamic performance.

2.1 Operational Stability and Performance of Air Suspensions on Various Vehicle Configurations. (Estill & Associates P/L, September 2000). (1)

Estill & Associates (1) report the results of a survey of 35 remote area operators (covering a broad range of commodity/body types) concerning experiences with the use of air suspension systems. The survey focused on “*operational stability and on-road performance of various vehicle configurations fitted with air suspensions*”. The operators were located in NT, Queensland, SA and WA.

The report found some evidence of operator safety concerns with vehicles using air suspension, but in relation to accident statistics concluded that “*Assessment of a limited number of accident records from one State did not indicate that vehicles using airbag suspension are over represented in accident statistics or have a higher accident rate than other vehicles.*”

The group of respondents “*had between 15–30 years experience driving spring suspension and between 5-10 years experience driving air suspension*”

The group of respondents generally preferred mechanical suspension as it provided better stability, required less steering and resulted in less trailer movement.

The group of respondents generally indicated that air suspension has a number of operational issues, including stability problems because of increased roll, sway and lurch of the vehicle, making it difficult for the driver to hold the combination in a straight line.

The main reasons for operators’ use of air suspension were:

- To gain increased axle mass
- To decrease commodity damage
- To improve driver comfort.

It was also stated by respondents that “*they preferred an air prime mover combination with spring trailers and dollies to lessen any sway or roll with the trailers.*”

The suspension of the prime mover was identified as critical in the overall stability of the vehicle combination. Mechanical suspension on both the dolly and trailer was found to positively effect the stability of the overall vehicle combination while air suspension was identified as negatively impacting on stability.

Drivers reported “*that prime movers with air suspension follow every little indentation in the road and ‘wallow’ from side to side thus requiring countermeasures to the steering to keep them straight*”. It was then reported that these countermeasures “*have adverse effects causing the configuration to lose stability and roll (in some cases) or ‘lurch’ to a new position on the road.*”

Further, “*drivers of high centre of gravity loads (eg. livestock/freezer) also reported greater lean and roll with air prime movers. The stability of high centre of gravity vehicles is effected by the roll that is set up from the levelling of the air bags, which effects the total performance of the overall combination*”.

In relation to cornering, the majority of drivers believed that prime movers fitted with air suspension lean considerably more when going into a corner and hence cause the driver to correct, further affecting the second and third trailers in terms of roll and sway. Discussions with all operators reported that tandem air dollies move around more than

mechanically-suspended dollies and that they behave erratically under braking,. As a result, most operators identified a preference for mechanically-suspended dollies as they tended to keep the combination straight.

In relation to on road performance, drivers commented that:

- Vehicles were more difficult to control with air suspended prime movers
- More caution was exercised with air suspension, particularly when entering corners and rough undulating patches
- Wide single tyres have been installed on the steer axle to give wider tyre footprint and better handling and stability
- Wide singles promote greater recovery when returning from the unsealed hard shoulder to the sealed pavement.

It was also reported that *“the majority of respondents stated that air suspension required more maintenance than spring suspension”*. However, review of additional material for tankers provided by Estill & Associates indicates that, although the air suspension itself generally has higher maintenance costs, the total vehicle maintenance cost is decreased with air suspension.

It was reported that industry is implementing modifications to air suspensions (particularly the prime mover drive suspension) to improve their performance in the areas of increased stability and drive traction. These modifications typically involve the fitting of additional ride height control valves (so that each axle operates independently) or large pipe work to improve air flow between the front and rear air bags.

Estill & Associates made the following recommendations:

1. Additional field research be undertaken in relation to the performance and stability of air suspensions when used in multi-combination configuration in relation to:
 - Configurations with 2 or more trailers
 - Operation on rough sealed and unsealed roads
 - Stability on narrow pavements tracking on and off the sealed section
 - Effect on stability using low profile and wide single tyres fitted to steer axles
 - Stability on close curved road alignment
 - Determining centre of gravity (COG) height limits
 - Trailer movement/on road characteristics for configurations incorporating air prime movers versus spring prime movers; and
 - Effect of speed and COG on configurations with air suspensions versus configurations with steel suspensions
2. Investigate and evaluate “after market improvements” to air suspensions
3. Encourage manufacturers to work with the transport industry in developing best design practice (eg location of shock absorbers, ride height valves etc) to improve performance of air suspensions applicable to multi-combination configurations
4. Improve accident collection techniques to include suspension types in accident questionnaires in order to develop a historical file on accident patterns.

In order to investigate problems raised by operators further analysis of Estill & Associates information was carried out. Consideration of the most frequently involved types of equipment showed that:

- 9 of the 35 prime mover drive suspension makes were Neway (the particular model was not listed)
- 8 of the 35 prime mover drive suspensions were fitted with Hendrickson WD
- 15 of the 35 trailer suspension makes were listed as BPW
- 7 of the 35 dolly suspension makes were listed as BPW (this represents all of the air dollies)
- 7 of the prime movers were Mack Titan
- 4 of the prime movers were Kenworth C501
- 3 of the prime movers were Kenworth T950

As the incidence of these makes in road train operations is not known, it cannot be concluded that these makes are over-involved. Specific details of any modifications to these vehicles were not provided.

To summarise the Estill & Associates report:

- Air-suspended prime movers were reported to deviate due to road surface variations
- Air-suspended prime movers also were reported to roll excessively especially with high COG trailers; the levelling of air bags was raised as a particular issue
- When excessive correction of the prime mover is required this adversely affects the roll and sway of the road train trailers
- These adverse effects on the trailers are reduced with mechanical suspension fitted to the dollies and trailers, rather than air suspension
- To overcome the steering control problems reported, operators have applied countermeasures including wide single tyres on steer axles, modified height control valves, modified air lines and more cautious driving style.

2.2 Investigation into the Specification of Heavy Trucks and Consequent Effects on Truck Dynamics and Drivers: Final Report. Report prepared for DoTRS by Roaduser International P/L (2)

Sweatman and McFarlane (2) investigated, in a systematic manner, the handling and ride performance of a group of trucks that had previously been reported as having poor directional behaviour and ride characteristics. The process undertaken is summarised as:

- Advertisements were prepared and published inviting vehicle owners within the target range of vehicles and with safety-related complaints to make contact with Roaduser
- Complainants were interviewed by phone to obtain information on their vehicles, and information on the behaviours that they considered were a safety problem
- All files held by DoTRS with regard to complaints about alleged unusual truck behaviours were reviewed, and notice taken of any information that would potentially assist with the investigation
- Drawing on the total list of complainants, a selection of vehicles was identified for an inspect-and-drive program that was undertaken by a senior Driver Education Centre of Australia (DECA) instructor
- Vehicles were selected for instrumented testing
- Vehicles were instrumented and driven, utilising the same trailer, load and test route
- Test data was processed and analysed to investigate, ride vibration, vehicle dynamics behaviour, steering behaviour
- Computer simulation models were exercised to investigate the parameter sensitivities of certain aspects of vehicle dynamics and steering behaviour
- Where test results appeared to show a correlation with complaints, potential mechanisms affecting the test results were modelled and explored.

Key findings of relevance to the present study include:

- Handling deficiencies in prime movers caused by drive axle suspension characteristics such as roll steer and low roll stiffness (in this case a particular model air suspension was highlighted)
- The use of regulation or other means should be considered to identify and control certain characteristics of suspensions and steering systems fitted to the front axles of prime movers with regard to their influence on unwanted steering disturbances and bump steer in particular.

Key vehicle mechanisms identified in (2) that could be present in vehicles highlighted in (1) include:

- Low roll stiffness
- Positive drive axle roll-steer
- Bump steer at the steering axle
- Oversteer
- High understeer
- On – centre steering variability

- Large pressure differential between left and right side of the suspension (for dual ride height control systems).

These mechanisms are discussed further below based on the Investigation into the Specification of Heavy Trucks and Consequent Effects on Truck Dynamics and Drivers: Final Report (2).

2.2.1 Vehicle handling quality

Vehicle handling is the generic term for the interaction between the driver and vehicle with respect to directional control and the science of handling provides a logical framework to investigate road train handling issues.

The driver's steering inputs bring about certain vehicle responses which permit the vehicle to follow a desired path (to a reasonable degree of accuracy) and to correct for disturbances acting on the vehicle. Disturbances acting on the vehicle include (i) external factors such as roadway geometry, roadway unevenness and wind effects and (ii) "internal" factors which may bring about unwanted steering of the vehicle.

The driver senses certain visual and motion cues and acts, via steering inputs, so that the vehicle will replicate the envisioned path and/or motion, within certain bounds. The driver more or less continuously monitors the relationship between his or her intentions with regard to directional control and actual vehicle behaviour, as he or she perceives it.

Truck performance research has tended to concentrate on stability limits. The effect of prime mover handling on multi-combination vehicle performance has never been studied but it is likely that road train drivers are more sensitive to and aware of the interaction mechanism described above than drivers of less dynamically active vehicles such as semi-trailers and B-doubles. This is because excessive lateral and yaw motions of the prime mover are amplified in road train trailers.

2.2.2 Prime Mover Response to Steering

Generally, the prime mover response - expressed as the yaw rate or lateral acceleration - follows the steering input with some gain factor and some phase lag, depending on the frequency of steering input. For steady-state conditions, the gain of the vehicle response could vary significantly with vehicle speed or with lateral acceleration itself. This may be expressed using the Handling Diagram (12,13). Vehicle handling is defined in terms of understeer, neutral steer and oversteer. The Handling Diagram especially searches for "oversteering" behaviour.

Based on the Handling Diagram (Figure 1), the handling metric used is termed the Understeer Coefficient, K (see eqn 1) which is plotted on the chart x-axis against lateral acceleration on the y-axis. A negative slope represents understeering and a positive slope represents oversteering ("infinite" slope is neutral steering).

$$K = r.l/V - \delta \quad - (1)$$

Where r = prime mover yaw rate

l = prime mover wheelbase

V = vehicle speed

δ = front wheel steer angle.

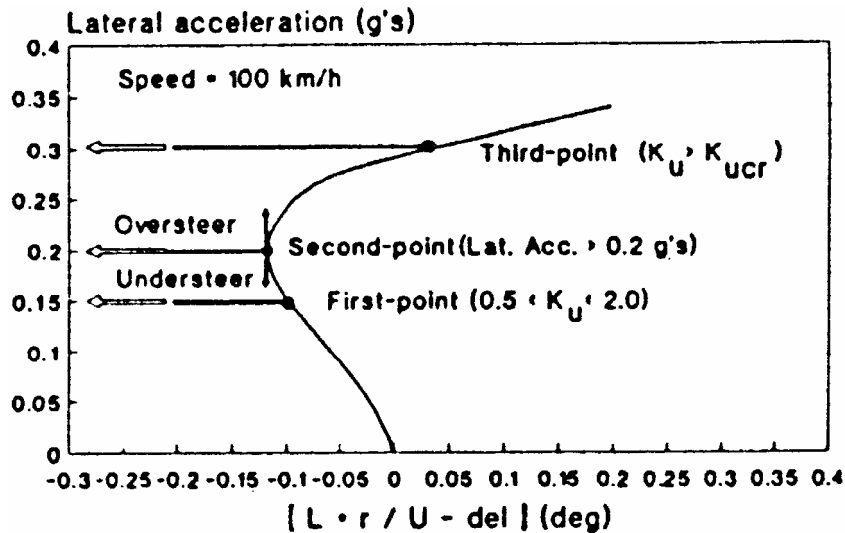


Figure 1 Handling Diagram (12)

In generic terms oversteer, understeer and neutral steer are defined as follows:

- Oversteer - means that the response gain of the vehicle increases with lateral acceleration, implying that the driver must reduce steering input to avoid excessive turning or deviation of the vehicle. The response will also have a delay due to the highly damped nature.
- Understeer - means that the response gain of the vehicle decreases with lateral acceleration, implying that the driver must increase steering input to avoid insufficient turning or deviation of the vehicle. The response will also be lightly damped and immediate.
- Neutral steer - means that the response gain of the vehicle remains constant with lateral acceleration, implying that the driver can hold a constant steering input to negotiate a turn

In general terms oversteer induces excessive but sluggish response while understeer induces lower sensitivity with “overshoot”. Trucks are designed to be understeering over the intended range of loading conditions. Understeering is considered by the automotive industry to be desirable for the wide range of car and truck drivers and only certain high-performance cars are designed to induce a degree of oversteer, providing higher sensitivity to performance limits for highly skilled drivers.

In (1), prime movers were described to “wallow” and “lurch” which may be drivers’ descriptions of oversteer and understeer.

Other mechanisms that may also be present in the road train prime movers and may be influence vehicle handling include:

- "Roll steer" of axles, which refers to unwanted steering caused by compression of the suspension on one side and extension on the other side of the vehicle
- "Roll stiffness" of suspensions, which refers to the amount of vehicle roll per unit lateral acceleration (for a given Centre of Gravity (COG) height)

2.2.3 Prime Mover Response to Disturbances

With regard to unwanted steering inputs disturbing the path of the vehicle, measurements can be made of the variability in front wheel steering angle (rms) and of the variability of drive wheel steering angle (rms).

A range of other truck "internal" characteristics, which could potentially affect either steering response or unwanted steering, can also be measured, including:

- The response of the steering system itself (from steering wheel to front wheel), in terms of both the gain and the phase lag
- "Bump steer" of axles, which refers to steering caused by deflection (compression or extension) of the suspension.

2.2.4 Suspension Roll Stiffness

Roll stiffness is defined as the rate of change in the restoring couple exerted by the suspension of a pair of wheels on the sprung mass of the vehicle with respect to change in suspension roll angle (11).

Roll stiffness may be viewed as a measure of the ability of a vehicle to resist body roll. It can be assumed that the total roll stiffness of a suspension is provided by two mechanisms. The first mechanism is the roll moment generated by the differential vertical deflection of the suspension springs and the second is known as the auxiliary roll stiffness. Auxiliary roll stiffness is provided by several means, varying from the incidental twisting of the suspension members to the action of deliberately placed anti-roll devices such as sway bars.

The relationship between the total roll stiffness and the two mechanisms that provide it can be described by the following equation:

$$K_{Rtotal} = K_{Raux} + \frac{K_V \times S^2}{2 \times \left(\frac{180}{\pi} \right)} \quad (2)$$

where: K_{Rtotal} = total roll stiffness (Nm/deg)

K_{Raux} = auxiliary roll stiffness (Nm/deg)

K_V = vertical stiffness of each spring (N/m)

S = lateral distance between springs (m).

When roll stiffness is low the driver may notice excessive roll or lean in curves of either the prime mover or trailers.

2.2.5 Suspension Roll Steer

The handling and tracking behaviour of heavy vehicles is affected by the suspension roll steer properties. When suspension roll occurs, the mechanical layout of many suspensions is such that the suspended axle tends to steer slightly. For example, when a trailing arm suspension rolls to the left, the left side of the axle moves back a little and the right side of the axle moves forward a little, resulting in axle steer to the left. The roll steer coefficient

is defined as the rate of change of axle steer angle with respect to change in suspension roll angle. The lower the roll stiffness, the more noticeable the roll steer effects will become.

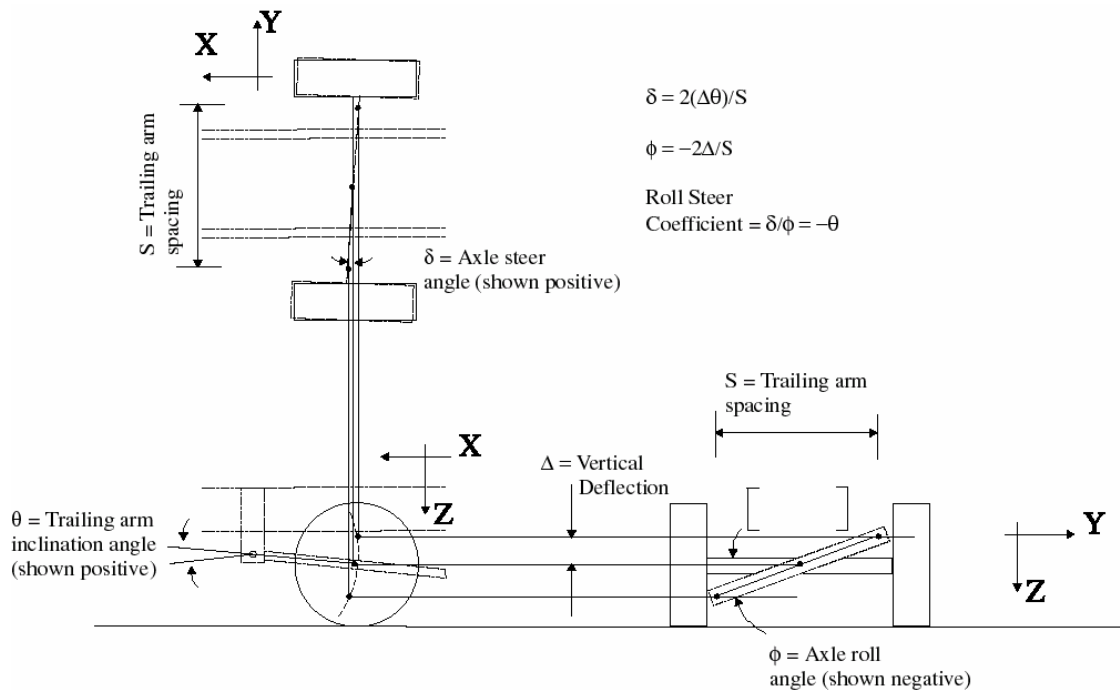


Figure 2 Roll Steer Definition

2.2.6 Tendency to Roll Over

Figure 3 illustrates the key factors in the tendency of heavy vehicles to roll over. Lateral acceleration acting on the COG creates a roll moment about the suspension roll centre, resulting in a suspension roll angle (depending on the suspension roll stiffness). This roll angle (which is also added to by axle roll) causes the COG to shift laterally.

The stability of the vehicle (proximity to rollover) is determined by moments acting about the ground plane. The destabilising moments are caused by:

- Lateral acceleration at the COG (with COG height as moment arm)
- Gravitational acceleration at the COG (with outboard COG shift as moment arm)

And the stabilising moment is caused by transfer of vertical tyre forces from the inner tyres to the outer tyres (with the track width as moment arm).

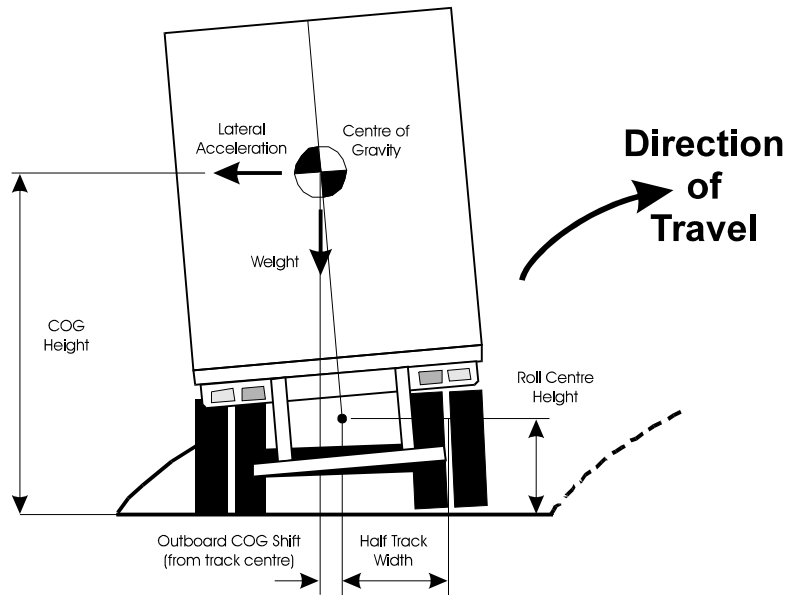


Figure 3 Vehicle Parameters that influence vehicle roll stability

The COG height is the single most powerful parameter and has two important effects:

- In its own right, on the destabilising moment caused by lateral acceleration
- Along with the roll centre height, on the destabilising moment caused by outboard COG shift.

Track width also plays an important role in determining the rollover stability of a vehicle. The track width is measured from the centre of left tyre set to the centre of the right tyre set. Wider tracks provide higher roll stability. Track width governs the stabilising moment generated by the transfer of vertical load from the inner tyres to the outer tyres.

Track width is indirectly limited by regulations governing maximum overall vehicle width. along with all maximum-axle-weight heavy vehicles, road trains employ the maximum track width available with dual tyres, which is around 1.83 m for an overall vehicle width of 2.5 m.

The other key parameter is the suspension roll stiffness, which affects the destabilising moment caused by outboard COG shift.

Trailer COG height is related to the following factors:

- Tare weight
- Payload
- Deck Height
- Overall Payload Height.

The payload centroid can be determined from deck height and overall payload height simply as the average of the two values. (ie Centroid height = (Deck height + Overall Payload Height)/2). The COG is typically lower than the centroid height and can be estimated using:

$$\text{COG Height} = (\text{Payload} \times \text{Centroid Height} + \text{Tare weight} \times \text{Deck Height}) / (\text{Payload} + \text{Tare weight})$$

In this case the empty trailer COG is estimated to be at the deck height. This may vary for body types such as stock crates and tanker vehicles. However, in general it is a good estimate of empty trailer COG.

The actual tendency to roll over during on-road operation of heavy vehicles also depends on the nature of manoeuvres undertaken. Generally, the lateral acceleration acting on the COG is not constant, but varies with time. Some manoeuvres (such as roundabouts) tend to approximate steady-state conditions, while others (such as sudden lane-changes) are transient and the time-varying nature of the lateral acceleration must be taken into account. This has two principal effects:

- At any point in time, the various sprung masses of a vehicle combination experience different values of lateral acceleration
- The roll inertia and yaw inertia properties of the vehicle need to be taken into account.

It should also be noted that road camber effectively introduces a lateral acceleration (in this case a component of gravity) that is proportional to the cross slope or camber.

2.2.7 Bump Steer

In most typical heavy vehicle steering systems, a linkage (usually called a drag link) transfers the steering action from the power steering gear on the vehicle body (or chassis) to the wheel steering arms on the front wheels (Figure 4). The steering action is achieved by the transitional displacement of the drag link in the presence of arbitrary suspension motions while the vehicle travels down the road. In the steering system there is also the potential for a steering action to result from the steer axle suspension vertical displacement. The steer axle suspension will deflect upwards (jounce) when going over a bump and downwards (rebound) when driving through a pothole. The steering that results from the vertical suspension displacement, is commonly referred to as steering geometry error (11) or 'bump steer'.

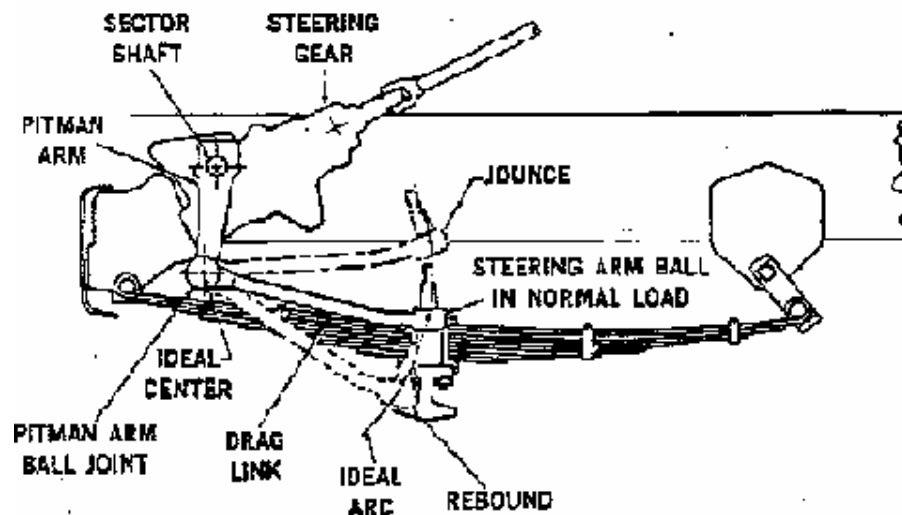


Figure 4 Ideal motions of the drag link during suspension articulation

In an ideal heavy vehicle steering system the drag link is designed such that the arc described by its ball connection to the steering arm exactly follows the ideal arc scribed by the front suspension during jounce-rebound deflections (Figure 4) (12). In this case, we can see that no steering action will result during the normal ride and handling motions of the suspension.

In practice it is not always possible to achieve this ideal because of packaging problems, spring variability, nonlinearities in the motion of the suspension and because of geometry changes at non-zero steer angles. Consequently, steering geometry errors will almost always occur and this will generally result in a change in toe angle with suspension deflections, a systematic steer at both wheels, or a combination of both.

Steering geometry errors (or bump steer) act as steer inputs from the normal vertical motion of the steer axle suspension and may result in steering vibrations or steering wheel 'fight'.

On-centre Steering Variability

On centre steering variability is essentially a change in steering ratio while a vehicle is tracking a relative straight path. This variability can be caused by:

- Lack of maintenance including in correct steering gear adjustment
- Steering system design
- Component wear.

When the vehicle tracks a path which requires large variation in steering wheel angle the steering ratio will change. It is possible for trucks to have a large ratio for small steering wheel angles and lower ratio for large steering wheel angles. The reverse is also possible.

2.2.9 Air suspension Pressure Differential

A large pressure differential between the two sides of the suspension could be due to (i) incorrect ride height system adjustment in systems employing dual ride height valve systems or (ii) inherent friction in the anti roll mechanism which can cause the system to bind up. This causes the introduction of a roll moment in the suspension which is reacted by different bag pressures on the left and right side of the vehicle. The influence of this on vehicle performance is largely unknown and was considered in the present study.

2.2.10 Measurement of Performance

In order to quantify vehicle performance it is necessary to make measurements of key vehicle control inputs and responses. The following control inputs were measured as part of the investigation undertaken in (2):

- Steering wheel input – this gave insight into the difficulty and variability of the steering task
- Wheel steer angle (relative to chassis) – this allowed determination of accuracy of the steering commands to front wheel steering input and steering gear ratio
- Bump steer – this allowed determination of unwanted steering of the front wheels
- Drive axle roll steer - this allowed determination of unwanted steering of the drive wheels.

The following prime mover responses were measured:

- Lateral acceleration² – this allowed determination of the lateral deviations of the prime mover. The Root Mean Square (RMS) value of the lateral acceleration is used to show variation in prime mover lateral deviation.
- Yaw rate³ – this allowed determination of yaw (or heading angle) deviation of the prime mover. Again the RMS value of yaw rate is used to show variation in prime mover yaw

The handling diagram was measured and computed (using the techniques outlined in Section 2.2.2) in normal operation and proved highly “diagnostic” for each vehicle in (2). This allowed the determination of understeer and oversteer behaviour. Air pressure was also measured dynamically with high response sensors. This allowed determination of mean and RMS values.

The main points for the road train investigation are:

- Air suspended prime mover handling deficiencies can be caused by drive axle suspension characteristics such as roll steer and low roll stiffness
- A particular suspension investigated had low roll stiffness and a degree of roll steer and is present in the road trains investigated in (1)
- Unwanted steering response can be caused by bump steer
- Handling deficiency can be successfully measured.

2.3 Manufacturer’s Guidelines on Application of Air Suspensions.

Discussion with major suspension suppliers and truck manufactures indicates that very few guidelines on the application of air suspensions are available.

Discussion with suspension manufacturers highlights that air suspensions are typically integrated with the vehicle unit on an individual basis. It is the vehicle unit manufacturer’s responsibility to integrate suspension systems correctly into their product. This of course can be done jointly with the suspension manufacturer.

Two suspension guidelines documents were obtained and reviewed. The first is a Hendrickson Australia document on the “HAS Series Air Suspension”. The second is a some material supplied by Daimler Chrysler Australia on air suspension systems that are fitted to Freightliner Vehicles taken from the Freightliner Data Book (FDB).

The document “HAS Series Air Suspension” is essentially an application guide on the HAS air suspension. It details how the suspension can be used and details which model to choose for particular Gross Combination Mass (GCM). This guide specifies a maximum of 25 % off-highway work for particular models of HAS such as HAS 400 and HAS 460. Overall this is a simple yet effective guide to the application of this popular suspension system.

² Lateral acceleration - is acceleration perpendicular to the forward direction of the vehicle (ie left to right) and allows determination of lateral motion of vehicle chassis

³ Yaw rate - is the time rate of change of heading angle of the vehicle

Section 4 of the FDB discusses application ratings for 6x4 air suspensions. The FDB focuses on three suspension systems: the 40K Airliner (ie 40000 lb. rating proprietary Freightliner Suspension), the 46K Airliner and the Neway AD246. Issues such as off highway use and high COG are discussed. It has been noted that customer reaction varies with high COG loads for the Neway product. Typical maximum rating is 140 t, based on axle capacity rather than suspension capacity.

For various purposes including warranty, suspension manufacturers tend to define road surfaces according to :

- Highway – sealed good quality surface
- Off-highway – unsealed good quality well maintained surface (regularly graded and repaired)
- Off-road – unsealed poor quality surface typically lightly trafficked no maintenance.

2.4 An Operational Field Test of Long Combination Vehicles Using ABS and C-Dollies. The University of Michigan Final Technical Report UMTRI-95-45-1. (1995) (4)

To test dynamic stability of A-doubles/triples vs C-doubles/triples Winkler (4) used practical measurements in the field. Winkler extensively investigated the operational performance of Long Combination Vehicles (LCV) over an 18 month period, with five commercial fleets operating in the northwest region of the US. The test fleet was fully instrumented and accumulated approximately 1.4 million miles during the study. The fleet consisted of seventeen tractors, eighty-six trailers and twenty-eight dollies that were configured as either double or triple combinations.

The C-dolly (Figure 5) is a double drawbar dolly that approximates a B-double fifth wheel trailer connection.

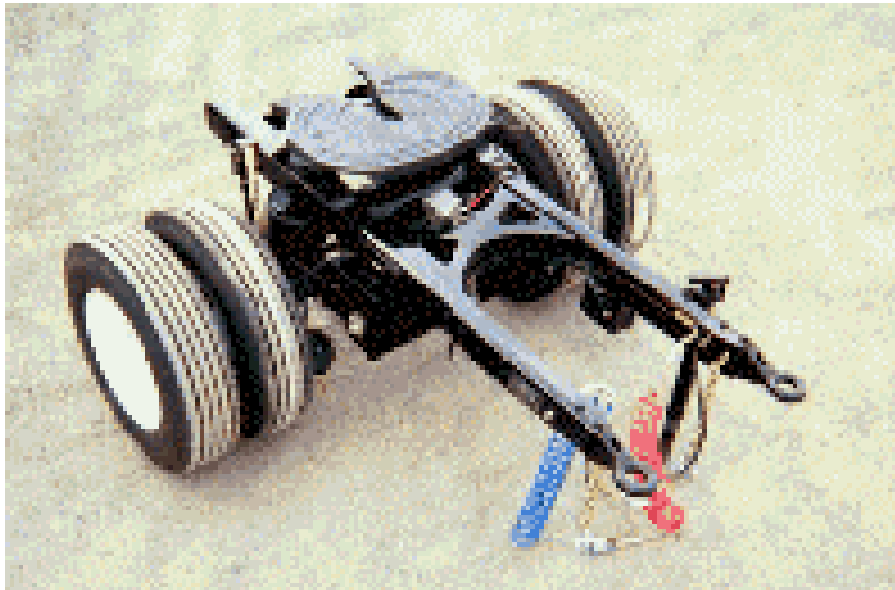


Figure 5 Typical C-dolly (US and Canada)

Winkler instrumented the combinations with the following instrumentation:

- Longitudinal acceleration (tractors only)
- Lateral acceleration (tractors and trailers)
- Wheel rotation speeds (all wheels)
- ABS supply voltage
- ABS modulator current
- Service brake air pressure
- Brake actuation pressures
- Steering activity of C-dollies

All data was collected autonomously with little or no delays to fleet operations.

The main measures used to investigate C-dolly behaviour were lateral acceleration and rearward amplification.

The main purpose of the study was to investigate ABS and C-dollies (double drawbar dollies) in LCVs. The main conclusions from the study in relation to the lateral trailer behaviour are:

- C-dollies serve to improve dynamic stability of double and triple trailer vehicles by reducing rearward amplification response
- When operating with A-dollies, the trailers of the LCV study vehicles tended to experience substantially larger lateral accelerations than the tractors towing them (ie amplification)
- When equipped with C-dollies, this tendency was greatly reduced or reversed (ie suppressed).

This research proved that the rearward amplification mechanism is present in vehicles while travelling on the road. Winkler found that, for A-dolly combinations, if the lateral acceleration at the lead unit varies by a certain amount the rear unit will be variable by a greater amount (ie amplification will occur).

Other insights into driver behaviour include that drivers compensated for the poor-performing A-dolly combinations by spending a smaller amount of time at higher lateral accelerations. That is, drivers are aware of the rearward amplification mechanism in their vehicle and react by applying less input at the front of the vehicle. Data presented in the report indicates that A-triple drivers apply approximately 50 % less 0.15 g events to their vehicle at the tractor than drivers of tractor semi trailers. This may explain why air suspended vehicles with poor performance are not necessarily over-represented in accident statistics.

2.5 On Road Dynamic Performance Testing of MAD and MAP Vehicle Combinations (Roaduser Systems 2001) (3)

McFarlane (3) investigated the dynamic performance of five multi combination grain transport vehicles operating on typical road sections near Port Wakefield in South Australia. The performance of the five vehicles (Multi Articulated Dog (MAD) & Multi Articulated Pig (MAP)) was compared to an air-suspended B-double.

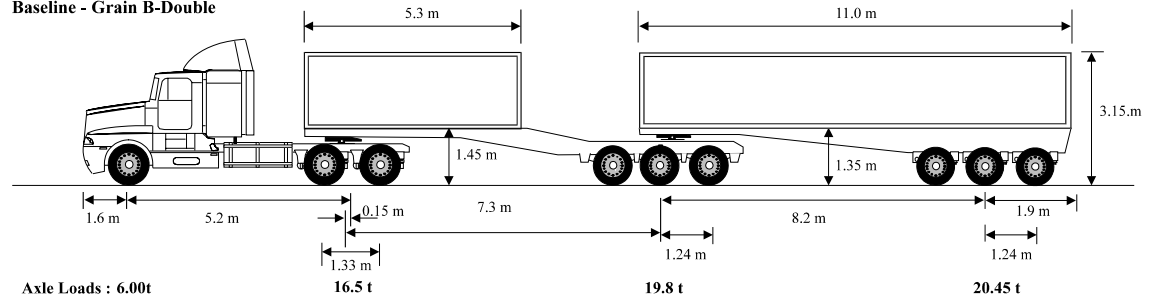
Table 1 details each vehicle specification in terms of suspension type for each axle group, overall length (OAL) and the measured GCM. A diagram of each vehicle combination tested is shown in Figure 6 with key dimensions and axle loads detailed.

Table 1. MAD and MAP Vehicle Specifications

VEHICLE NO.	VEHICLE TYPE	STEER AIR/MECH	DRIVE AIR/MECH	TRAILER 1 AIR/MECH	DOLLY AIR/MECH	TRAILER 2 AIR/MECH	OAL (m)	TEST GCM (t)
1	B-Double	Mech	Air	Air	-	Air	24.05	62.75
2	MAD1	Mech	Air	Air	Air	Air	24.80	62.10
3	MAD2	Mech	Mech	Air	Air	Air	24.88	62.25
4	MAD3	Mech	Air	Mech	Mech	Mech	24.89	63.70
5	MAD4	Mech	Mech	Air	Mech	Mech	25.00	62.85
6	MAP	Mech	Air	Mech	Mech	Mech	24.60	61.05

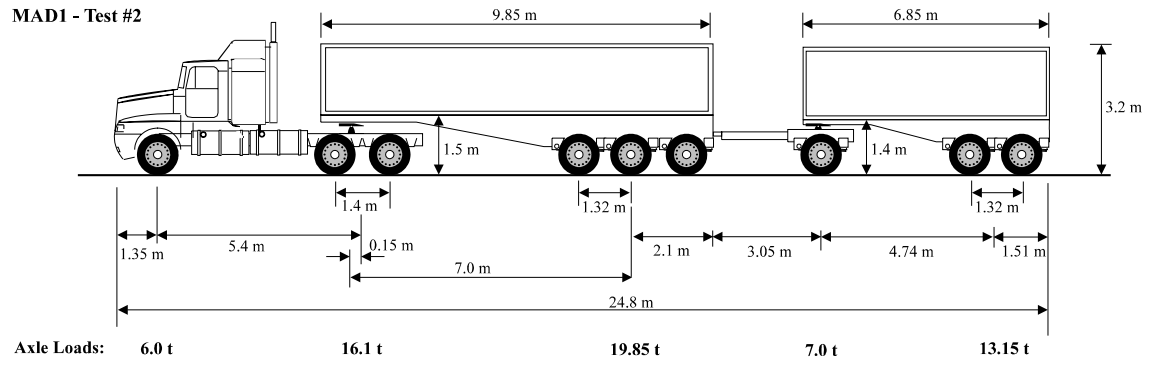
Vehicle 1 – B-Double

Baseline - Grain B-Double



Vehicle 2 – MAD1

MAD1 - Test #2



Vehicle 3 – MAD2

MAD2 - Test #3

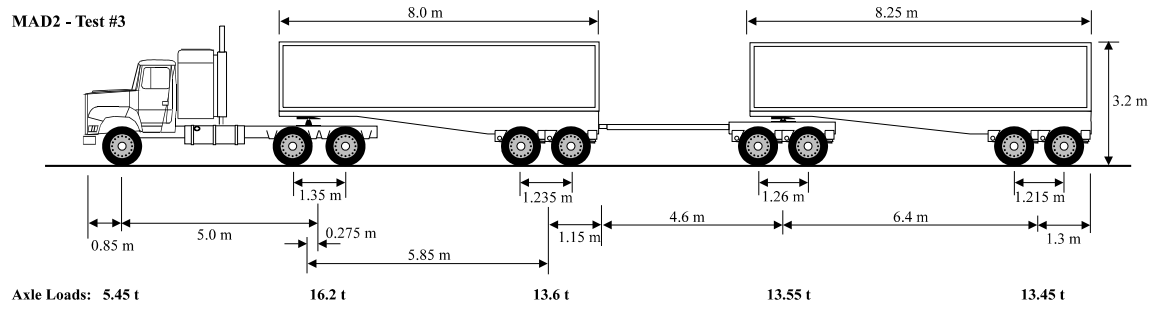
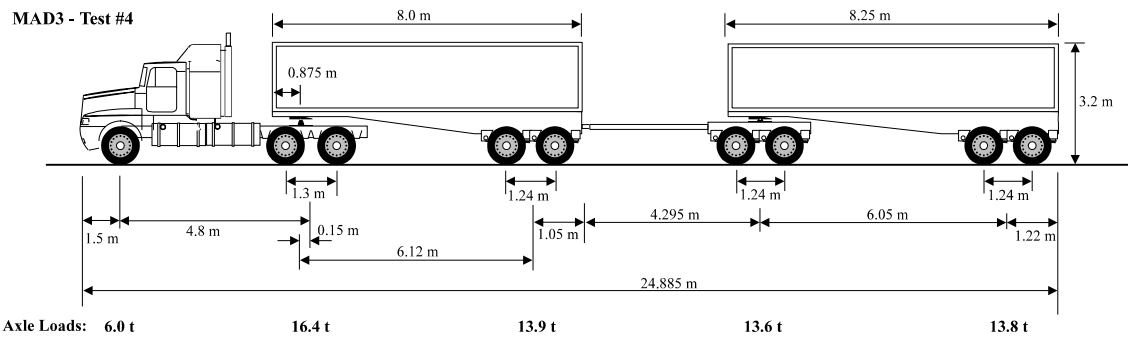
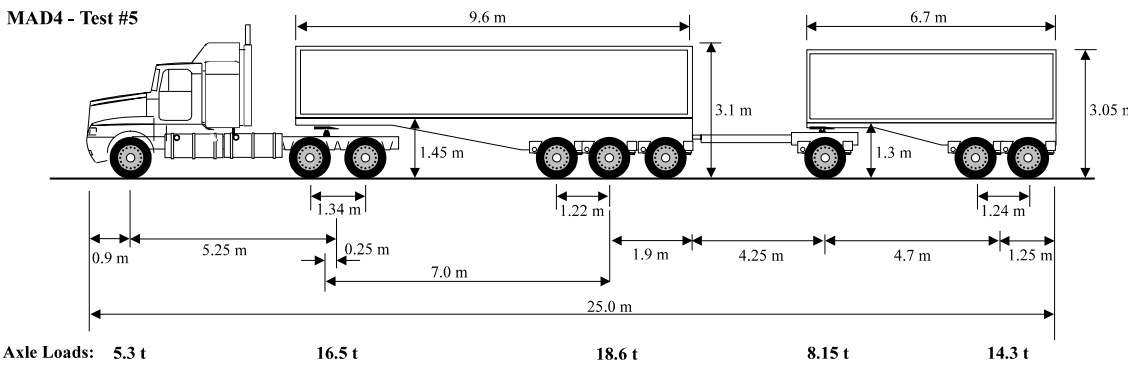


Figure 6 MAD and MAP Test Vehicles

Vehicle 4 – MAD3



Vehicle 5 – MAD4



Vehicle 6 - MAP

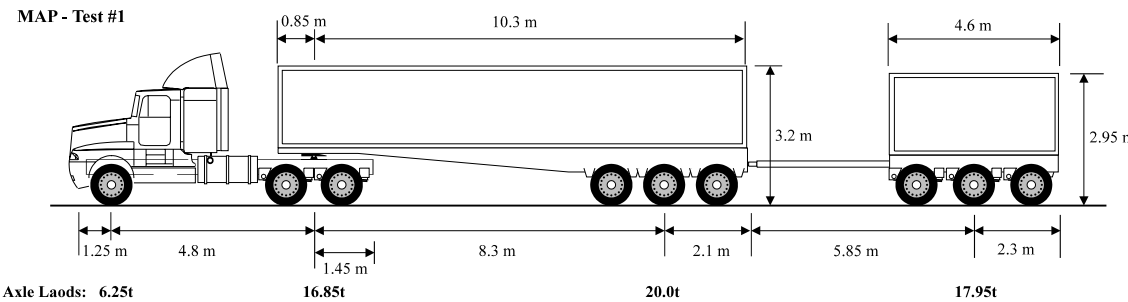


Figure 6 (cont) MAD and MAP Test Vehicles

As well as the route testing all vehicles were tested for performance in the SAE lane change and for yaw damping.

As in Winkler (4), McFarlane measured rearward amplification or amplification ratio successfully while travelling on the road.

McFarlane also showed that the B-double driver was less cautious about the vehicle performance since the B-double had superior performance relative to the other vehicles being tested. For example, the driver comfortably executed a yaw damping manoeuvre with a 0.40 g acceleration pulse. It was also observed that the driver engaged the cruise control at 100 km/h and drove the vehicle through all corners with the cruise control

engaged suggesting high confidence levels. This gave high average speeds and high steering input, yet low rearward amplification (0.95 -1.0).

A vital finding for the road train study is that the general performance of mechanical suspension with regard to roll stiffness was superior to that of the air suspensions investigated. The mechanical and air suspensions were typical of those used on multi-combination vehicles. It is also worthy of note that the suspension that exhibited the lowest roll stiffness was the drive air suspension of MAD1.

McFarlane concluded that:

- Suspension type had a significant impact on the performance of the MAD vehicle combination. Combinations with mechanical suspension had better performance. Suspension characteristics had more influence on the performance of the combination than did the drawbar length, trailer wheelbase and tow coupling overhang.
- MAD1 shows performance that was less than desirable and this was attributed to:
 1. Poor vehicle geometry (since the coupling overhang on trailer 1 was maximised and dolly drawbar length was minimised)
 2. Low roll stiffness of the prime mover, trailer and dolly suspensions.

MAD2 had very similar vehicle geometry to MAD3 yet MAD3 had performance significantly better than MAD2. MAD2 showed performance that was less than desirable and was caused by low roll stiffness of the trailer and dolly suspensions.

With regard to the road train study, the main points are:

- Mechanical suspension performed better than air suspension
- The driver was less cautious with the best vehicle (B-double)
- Suspension is the most important factor and roll stiffness is a key player
- On-road rearward amplification measures showed that, with air suspension, motions at the prime mover were significantly amplified (up to 2.5 times) and this is 30 - 70% greater than the amplification with the mechanically-suspended units
- Yaw damping was difficult to measure in on-road tests, due to (i) difficulties with different drivers producing the same steering pulse input and (ii) analysis difficulties related to the “background” disturbances from road roughness and other sources.

2.6 ARTSA Air Suspension Code - Guideline for Maintaining and Servicing Air Suspensions for Heavy Vehicles, May 2001

This text is relevant to many levels in the heavy vehicle industry, including management, service and maintenance or day to day operations. Mechanisms such as roll stiffness, roll steer and function of shock absorbers are clearly defined.

Key points taken from the guide include:

“Air suspension may not suit all transport applications. In some instances the driver is not able to “feel” how the vehicle or combination is handling, as generally occurs with conventional mechanical suspensions.”

“By itself air suspensions have poor roll stiffness and require anti-roll devices to be included”

“The handling and tracking behaviour of heavy vehicles is affected by the suspension roll steer properties.”

“The lower the roll stiffness, the more noticeable the roll steer effects will become.”

“Roll centre height may be viewed as directly affecting the “moment arm” from the roll centre to the vehicle centre of gravity (COG) height. The greater this moment arm (and the lower the roll centre height), the more the vehicle will roll for a given lateral acceleration applied to the vehicle COG.”

“Particular attention must be given to the choice of drive axle suspensions selected for high gross combination mass (GCM) applications.”

“One of the main options is the ability to fit additional anti-sway bars or other features to increase roll stability, especially for loading with high centre of gravity (eg. livestock and logs).” (Trailer Units)

“Operators have found that suspension component failure is greatly reduced by retorquing Ubolts during the first day of service following the initial tightening.”

2.7 Stability Of Heavy Vehicles With Increased Mass Limits For Dual-Tyred Single Axles and Road-Friendly Suspension, NRTC report prepared by Roaduser International, March 1999.

The focus of this study was the roll stability and lane-change performance of vehicles equipped with single axles in particular rigid trucks. The results from the study indicate that vehicles with single axles would benefit from increased maximum axle limits and conversion from mechanical to air suspension would improve vehicle performance. However, it must be realised that the mechanical suspension systems for single axle drive trucks typically have longer leaves, hence have a lower spring rate and lower roll stiffness than typical trailer mechanical suspensions.

It is also important to consider that there were no multi-combination vehicle dynamics issues to consider in the vehicles being assessed in this study. This study has little relevance to the issue of handling and dynamics of air suspensions in multi-combination vehicles.

2.8 Draft NRTC Report on Non-Air Road Friendly Suspension

This report identifies advantages with mechanical suspension systems over air suspension. The advantages include:

- Higher average roll-centre height than air suspensions
- Lower range in roll-centre heights

This report also identifies that:

- Trailer suspension roll stiffness and roll centre height are key to the dynamic performance of the trailer
- Mechanical road-friendly suspension systems have stability that is equivalent to or better than air road-friendly suspension systems.

2.9 Definition of Potential Performance Measures and Initial Standards, NRTC April 2001

This report contains performance measures that may form the basis of future performance based standards assessment criteria.

The core performance measures that may be relevant to the issue of multi-combination dynamic performance are:

- Static Roll Stability
- Rearward Amplification
- Load Transfer Ratio
- High Speed Transient Offtracking
- High Speed Steady State Offtracking
- Yaw Damping
- Tracking on Straight Path
- Braking Stability in Straight line
- Braking Stability in a turn
- Handling

However, it must be realised that these performance measures are usually based on computer simulation and are highly dependent on the data that is provided to the models. For some of the measures a significant amount of input data is required to correctly calculate the vehicle performance for the particular measure. For example vehicle handling is extremely complex and essentially relates input at the steering wheel to yaw response. However, the usual method of calculation essentially results in the elimination of the steering mechanism from the system and this could be a major influence with problem vehicles.

Table 2 lists each of the performance measures and comments on their relevance to multi-combination dynamic performance.

Table 2. Relevance of Performance Based Standard Measures

Performance Measure	Comment
Static Roll Stability	Relevant yet unlikely to show that air suspended trailer is much worse than mechanically suspended trailer
Rearward Amplification	Relevant and easy to test, likely to show performance deficiency as shown in (3),(4); a better measure for road trains if amplification is measured at more than one frequency
Load Transfer Ratio	Relevant yet impossible to test. Simulation results have never been validated
High Speed Transient Offtracking	Relevant and easy to test; likely to show performance problem
High Speed Steady State Offtracking	Not easy to test for; essentially designed to test adequacy of road width
Yaw Damping	Relevant and potentially easy to test; practical problems in making the required measurements and analysing results, as occurred in (3)
Tracking on Straight Path	Difficult to accurately quantify; measure is road width required not tracking; essentially designed to test adequacy of road width
Braking Stability in Straight line	Relevant yet complex to test and simulate
Braking Stability in a turn	Relevant yet complex to test and simulate
Handling	Relevant yet complex to test and simulate; has previously shown performance problem (2)

2.10 Organisation for Economic Co-operation and Development (OECD) Technical Report on Dynamic Interaction between Vehicles and Infrastructure Experiment (DIVINE), 1998

Focus of this research was on infrastructure wear issues rather than handling and dynamics of multi-combination vehicles. A key point of some relevance was the statement that:

“It is recommended that a suspension be considered road-friendly if the natural frequency does not exceed 1.5 Hz and the damping is at least 20 per cent of critical”

The decision was made in Australia to adopt the European requirement of 2.0 Hz maximum frequency and 20 % damping. It must also be realised that there are likely to be air suspensions manufactured prior to the implementation of road-friendly requirements that are not likely to meet the 2.0 Hz and 20 % damping criteria and some could be present in the multi-combination vehicle fleets in question.

2.11 Handbook of Vehicle – Road Interaction, David Cebon, 1999.

This text focuses is on road damage mechanisms rather than dynamics and handling issues. Vehicles investigated are typically European in configuration. The main chapter of relevance to the road train suspension study is Chapter 4 Suspension Components, but there is no discussion of issues such as roll stiffness or roll steer. The issue of shock absorber wear and function is covered and test data collected indicates *“that some air suspensions are likely to have poorly maintained or incorrectly fitted shock absorbers”*.

Suggestions for future suspension design of relevance from Cebon are:

- *“Suspensions should have low vertical stiffnesses while maintaining adequate roll stability.”*
- *“Dry friction should be minimised. This reduces dynamic loads and generally improves static load sharing in axle group suspensions. Suspension damping should be provided by hydraulic shock absorbers.”*
- *“Centrally-pivoted suspensions (eg walking beams) should have sufficient viscous damping to prevent damped tandem pitching motion.”*

There is no emphasis on multi-combination vehicle dynamics in this text.

Suggestions for future vehicle regulation of relevance are:

“A suspension assessment programme should include two components: an initial type approval test, performed on each vehicle (or suspension); and an annual inspection to confirm compliance with in-service damping requirements.”

3. DISCUSSION OF LITERATURE

3.1 Handling

Heavy truck handling is a complex issue and has received limited research attention. Previous work (2) has shown that vehicle handling analysis is capable of highlighting vehicle performance issues. However, the vehicles investigated were prime mover semi-trailers. The effect of understeer and oversteer behaviour of a prime mover on multi-trailer dynamic performance has never been investigated. Prime mover handling is known to be affected by only the first unit in the combination therefore performance deficiencies in the second and third units are unlikely to affect prime mover handling. However, the reverse will not apply: Prime mover performance deficiencies will affect tracking and stability of the subsequent trailers.

It is likely that the performance baseline of road trains has shifted: the introduction of air suspension on road train prime movers may have increased the amount of movement of the front of the vehicle by 20 – 30 % (through roll steer and low roll stiffness). The introduction of air suspensions on the trailer has been shown (3) to degrade performance by 30 – 70 %. The combined effect of this could see vehicle performance for particular attributes degraded by 50 – 120 %.

3.2 Roll Stiffness and Roll Steer

From the review of the anecdotal evidence contained in (1) it is evident that many of the operators are describing issues that could relate to low roll stiffness or insufficient roll stiffness for the body/commodity type being hauled. It is also evident that roll steer is likely to be a further potential cause for the described behaviour.

The field testing conducted in (3) indicated that mechanical suspensions have high roll stiffness and high roll centres. The analysis undertaken in (7) further confirms this result. These results change the perception of performance differences between air and mechanical suspensions. However, the air suspension on the vehicles investigated in (3) may not be representative of the types of air suspension used for road trains.

Eight of the 35 vehicles detailed in (1) are fitted with Hendrickson WD suspension on the prime mover. This suspension system was previously found (2) to have low roll stiffness and roll steer which caused a particular vehicle investigated to have non-understeer behaviour. It needs to be considered whether these mechanisms could be present in the vehicles in question.

Nine of the 35 vehicle detailed in (1) are fitted with Neway suspension on the prime mover.

3.3 Measurement of Performance

The literature shows clearly that vehicle performance can be measured while the vehicle is on the road. It is not necessary to perform the testing on a test track or under isolated conditions. This is important because the complexities of testing road trains on test tracks makes it extremely time consuming and logistically difficult (ie finding a test track or road site large enough to get the vehicle up to speed, manoeuvring, etc).

The following is a summary of previous vehicle mechanisms that have been measured and are likely to show performance deficiencies in multi combination vehicles:

- Rearward Amplification – has been measured on the road and on track. On road measurement has the advantage that driver skill is less important (ie does not have to follow lane-change path). The measure has been proven to be effective in determining performance deficiencies and has also been measured autonomously with few operational interruptions.
- Handling – has been measured on road and on track. Road measurement is advantageous in that road disturbances are present to highlight other vehicle deficiencies or triggering events
- Bump steer – has been measured on road and on track. Road measurement is advantageous in that realistic data is collected.
- Roll Steer - measured on road and on track. Road measurement is advantageous in that realistic data is collected.

3.4 Suitability of Air Suspension

The literature indicates that some air suspension systems when used in a multi-combination vehicles may be unsuitable for the body/commodity type being hauled due to:

- Low roll stiffness / roll centre (both drive and trailer axles)
- The presence of roll steer (both drive and trailer axles)
- Insufficient or low suspension damping (both drive and trailer axles).

While the material reviewed suggests that poor driver feel is exhibited by air suspensions it is unlikely to be the primary cause of stability issues with multi-combination vehicles.

There is some evidence to suggest that drivers are more sensitive to less stable vehicles and adjust their driving styles accordingly but there is very little information to confirm this for road train drivers. It is likely that road train drivers (due to rearward amplification) are more sensitive to anomalies in vehicle performance and have greater visual cues (ie rear trailer movement, sway, etc).

3.5 Mechanisms for Investigation

Based on the literature, the following vehicle mechanisms were selected for investigation with respect to road train dynamics:

- Oversteer/ understeer
- Prime mover steer axle bump steer
- Low roll stiffness (both drive and trailer axles)
- Roll steer (both drive and trailer axles)
- Insufficient or low suspension damping (both drive and trailer axles).

3.6 Performance Based Standards

Review of the potential performance based standards has highlighted that of the ten core standards being considered three are likely to have the ability to highlight performance deficiencies in road trains:

- Rearward amplification
- Vehicle handling (oversteer/understeer)
- Yaw damping.

Vehicle handling and dynamic performance problem solving is essentially diagnostic and investigative by nature. In contrast, PBS assessment involves the determination of vehicle performance to a broad set of standards, to filter out poor performance. Also, it may be necessary during this type of assessment to exclude (due to a lack of sufficient detail available from suppliers) some vehicle mechanisms.

4. PROBLEM VEHICLES AND MODIFICATIONS

The owners and operators of problem vehicles represented in the Estill Report (1) were contacted by telephone to discuss the nature of the handling problems encountered, the specifications of their vehicles and any modifications which had been undertaken. In all, 18 operators were contacted.

Generally speaking, it was not possible to obtain a great degree of engineering detail and in some cases circumstances had changed because a significant period of time had elapsed since the Estill survey.

The results of Roaduser's review of the problem vehicles will be presented in terms of:

- The nature of the problems reported
- Solutions which may have been adopted
- Engineering characteristics of problem vehicles.

Consideration will also be given to performance measures which best relate to the problems raised.

4.1 Problems Reported

The biggest complaint, although expressed somewhat differently by respondents, was poor dynamic tracking behaviour. This was variously described as: poor tracking, poor dynamics, swaying, wagging, wandering, leaning, erratic tracking, hanging down and poor feel. This group of problems applies to the entire combination (not just the prime mover).

A related persistent complaint was that it was necessary to reduce speed to overcome the problems of poor dynamics.

A further significant complaint was shock absorber performance. This complaint refers to air suspensions almost by definition because shock absorbers are not fitted to trailer mechanical suspensions. The complaints include:

- Poor performance of shock absorbers in that they fail to damp out undesirable trailer motions
- Premature wear and failure of shock absorbers

and again these complaints refer to the entire vehicle combination.

Some operators complain of dangerous behaviour on the road and report accidents which have been caused by poor dynamics. Reported dangerous behaviour includes excessive roll and excessive swaying of trailers.

Some operators also complain of difficulties in learning to drive combinations safely and the dangers of using drivers who are unfamiliar with the vehicles in question.

A significant group of operators also reported problems with component failure, premature wear and excessive maintenance requirements, including:

- Shock absorber failure
- Air bag failure

- Steering pump failure
- Tyre chop-out
- Need to adjust the suspension weekly.

4.2 Solutions Implemented by the Road Train Industry

One basic response to the problems raised was simply to reduce speed of travel. Speed restrictions had been introduced by several operators.

Most of the mechanical interventions undertaken by operators related to suspension modifications. These modifications covered both the prime mover and the trailers and included:

- Introducing larger air lines in the prime mover suspension in such a way that longitudinal air flow between axles is increased; this should improve the load-sharing capability of the suspension; in both cases where this was implemented, it was reported to fix the problem
- Conversion from dual ride height controls to a single ride height control valve on prime mover air suspension; this should assist in equalising air pressures on both ends of the axle and therefore equalising spring rates; in one case where this was implemented, it was reported to fix the problem
- Replacing the OE trailer suspension ride height control valve with a valve of higher strength and durability; in rough conditions, valve failure can occur and lead to trailer sway problems; in one case where this was implemented, it was reported to fix the problem
- Relocating the trailer air suspension shock absorbers to a vertical orientation; in one case where this was implemented, it was reported to reduce trailer sway.

One operator changed the prime mover's steering box (which was suspected to be faulty) at the same time as changing the prime mover suspension ride height control valves. The operator reported that the problem was fixed, but it is not known which change (or both) contributed to the improvement.

Some operators made significant attempts to overcome problems with air-suspended dollies. One operator installed an additional ride height control valve on a tandem air dolly so that each axle was controlled independently; this was reported to fix the problem. Another operator reported that it was difficult to fix air-suspended dollies, and another reported that he had converted back from air to mechanically-suspended dollies.

One livestock operator converted four sets of road train trailers from air to mechanical suspension and fixed the problems he was experiencing. The combinations continued to operate at the same weights, due to volumetric loading.

4.3 Characteristics of Vehicles Investigated

All of the vehicles investigated had air suspensions fitted to the trailers. Most of the prime movers (but not all) had air suspension. Some of the dollies had air suspension.

In relation to converting back from air to mechanical suspension, this only occurred on trailers and dollies. None of the prime movers were converted to mechanical suspension.

4.3.1 Trailer characteristics

All of the trailers discussed in the Roaduser contacts had BPW air suspension, and the majority of these utilised the (stronger, more roll-stiff) square axle. It should be noted that BPW air suspension appears to be highly-represented in road train trailers and BPW is not necessarily over-represented in the complaints. BPW air suspension seems to be generally well-respected by road train operators.

With regard to body types, the following list progresses from the most prevalent to the least prevalent:

- Livestock (which combines high mass under volumetric loading, high COG and generally shorter wheelbase)
- Tipper (which generally has shorter wheelbase)
- Flat-top
- General freight
- Tanker, dry bulk tanker and container.

Again, it is likely that livestock and tipper body types are highly-represented in road train operations, so they are not necessarily over-represented among the complaints. However, it would appear that livestock trailers in particular have good reason to be over-represented in road trains with handling problems (because they have high mass and high COG).

4.3.2 Prime mover characteristics

A significant number of the prime movers had either Hendrickson WD2 or Neway air suspension. These suspensions are a common choice for road train prime movers and are therefore not necessarily over-represented. However, as discussed in the literature review, the Hendrickson WD2 has been previously found to be associated with undesirable handling characteristics.

The vast majority of prime movers operated by the complainants and identified as being involved in problem combinations were Kenworth. It is likely that Kenworth prime movers are highly-represented in road train usage and are not necessarily over-represented in the complaints. However, the Kenworths involved tend to utilise Hendrickson WD2 suspension, and, as discussed in the literature review, some Kenworth prime movers were previously found to exhibit significant bump steer. Other prime mover makes represented in the problem combinations are: Mack, Volvo, Ford, International/Iveco and Western Star.

Prime mover wheelbases are in the range 5 m to 6.2 m.

Most of the prime movers involved in problem combinations have multi-leaf front (steering axle) suspensions.

4.3.3 Dolly characteristics

Dollies were characterised by suspension type and drawbar length. Most of the dollies used in the complainants' combinations were air-suspended, and - in terms of problem combinations - the vast majority are air-suspended. As there appear to be relatively few air-suspended dollies in road train service, air-suspended dollies appear to be over-represented in problem combinations.

Drawbar lengths were characterised as “short” (less than 4 m) and “long” (4 – 5 m); both the complainant combinations and problem vehicles were reasonably equally split between short and long drawbars, and this does not appear to be a major factor.

4.4 Relevance of Performance Measures

Performance measures which may assist in quantifying the dynamic performance of road trains in relation to the problems raised above may be drawn from (i) the current Austroads/NRTC PBS project and (ii) other research discussed in the literature review.

4.4.1 Relevant PBS measures

Table 3 lists the currently-proposed PBS measures along with their likely relevance to detecting road train dynamic performance issues as raised and described by road train operators; the performance measures are described in Annex A. With some exceptions, currently-proposed PBS measures for road trains are not particularly relevant to the problems identified. The most relevant PBS measures are:

- Handling, which speaks to the controllability of the prime mover
- Yaw damping, which speaks to the tendency for trailer swaying motions to persist
- Rearward amplification, static roll stability and load transfer ratio (although the SAE standard lane-change manoeuvre, with a single, relatively high frequency, is of limited use for Australian road trains)

and three other measures (high-speed transient offtracking, high-speed steady-state offtracking and trailing fidelity) also have some limited relevance to the problems raised.

Table 3. Potential Measures – PBS Project

Performance Measure	Likely Effectiveness for Problem Combinations
Static Roll Stability (SRS)	Applies to individual vehicle units, so only addresses part of the problem. High-COG, high-mass trailers will show low SRS. SRS will also show suspension effect.
Rearward Amplification (RA)	Applies to vehicle combination. Relevant, easy to test and likely to show performance problems. Manoeuvre needs to be reduced in severity to allow meaningful comparison between road trains. Also only covers one steering frequency and may miss high amplification at other frequencies.
Load Transfer Ratio (LTR)	Addresses the dynamic stability of the combination. Most of problem road trains would roll over in the standard test manoeuvre proposed, so provides no useful measure in its current form. Also only covers one steering frequency and may miss high amplification at other frequencies. Latest proposal (15) is to delete from PBS.
High Speed Transient Offtracking (HSTOT)	Relevant to swaying issues and easy to test. Most of problem road trains would roll over in the standard test manoeuvre proposed, so provides no useful measure in its current form. Also only covers one steering frequency and may miss high amplification at other frequencies.
High Speed Steady State Offtracking (HSOT)	Not easy to test for; essentially designed to test adequacy of road width; steady-state rather than dynamic measure. While HSOT would provide some indication of problem vehicles, other measures would be more effective.
Yaw Damping (YD)	Relevant and potentially easy to test, although there are practical problems with on-road testing, as found in (3); this is considered to be a highly relevant measure.
Tracking on Straight Path	Difficult to accurately quantify, measure is road width required not tracking, essentially designed to test adequacy of road width; in some forms, this measure provides some indication of performance relevant to issues raised; such measures are best described as addressing trailing fidelity performance.
Braking Stability in Straight line	Relevant yet complex to test and simulate; not specifically relevant to problems raised.
Braking Stability in a turn	Relevant yet complex to test and simulate; not specifically relevant to problems raised.
Handling	Relevant yet complex to test and simulate; has previously shown performance problems; difficulties in controlling the prime mover are likely to be amplified in the trailer response.

4.4.2 Additional measures

An approach taken in (3) and (4) was to measure rearward amplification during on-road travel rather than in a lane-change manoeuvre. This has the advantages of:

- Obtaining a single measure which is relevant to the range of steering frequencies actually adopted by the driver (rather than a single frequency)
- Avoiding the need for an accurately-staged test manoeuvre, a suitable site for which may be difficult to locate
- Avoiding the use of a standard test developed for smaller, less dynamically active, vehicle combinations and which many road trains are unable to negotiate without rolling over.

This measure will be termed the Rear Amplification Ratio (RAR), and is determined from the lateral acceleration time histories of the prime mover and rear trailer, and is given by:

the standard deviation at the rear trailer divided by the standard deviation at the prime mover. The RAR provides a measure of the extent to which the lateral acceleration at the rear trailer exceeds that at the prime mover, under normal travel conditions and taking account of all frequencies of prime mover lateral motion; the prime mover motion frequencies are in turn affected by the steering frequencies input by the driver and other extraneous frequencies related to road roughness and other disturbances.

A further approach adopted in (3) was to compute the transfer function gain between the lateral acceleration at the prime mover and that at the rear trailer. This provides a picture of the rear amplification at each frequency of prime mover lateral motion or steering input. It was found that the transfer function gain typically has a value of 1 at low frequencies (zero amplification), rises to a peak at a certain frequency and drops off to values approaching zero at higher frequencies (2 Hz and above). The proposed PBS Rearward Amplification value refers to a single steering frequency of 0.4 Hz (as generated in a lane-change manoeuvre). The steering input used to obtain such a transfer function will be termed the frequency sweep.

Measurements of the frequency content of articulated vehicle driver steering behaviour (2) have shown that normal steering has a peak around 0.25 Hz and that, in more difficult steering control situations, a second peak around 0.5 Hz occurs.

Extensive US research (4) also measured rear amplification of multi-combinations under actual operating conditions. Measures which were found to be useful in relation to quantifying the stability-enhancing characteristics of improved trailer coupling arrangements included:

- The lateral acceleration transfer function gain described above
- The peak rear amplification obtained from the transfer function gain
- Comparison of front and rear histograms of lateral acceleration (percent of time spent above a certain lateral acceleration, front versus rear)
- A measure termed the lateral acceleration experience of trailers relative to the experience of tractors; this was computed as the ratio of the percent of time spent above a certain lateral acceleration value (trailer over tractor) plotted against lateral acceleration.

Taking into account the nature of the performance problems raised in the present investigation, the following additional measures were included for evaluation using computer simulation:

- The transfer function gain between the lateral acceleration at the prime mover and that at the rear trailer
- The peak lateral acceleration gain, and the frequency at which it occurs.

4.5 Additional Vehicle Parameters

While computer simulation of heavy vehicle dynamic performance typically includes a wide range of vehicle parameters, certain parameters were specifically added for the road train simulations in this investigation.

Taking into account the nature of the performance problems raised in the present investigation, the following vehicle parameters were specifically included for investigation in computer simulations:

- Suspension roll steer and roll centre height (both drive and trailer axles)
- Bump steer (at the steering axle)
- COG height of trailers
- Air suspension load sharing
- Dolly air suspension load sharing.
- Air suspension differential pressures (differing spring rates side-to-side)
- Air suspension damping (trailer axles).

All of these parameters are included in the discussion of the literature, with the exception of suspension load sharing. In order to qualify as road-friendly in Australia, air suspension must be capable of sharing the load within +/- 5 %. This usually refers to static or low-speed load sharing. At higher speeds, in dynamic situations, the mean axle loads should be within +/- 5 %. However, the nature of some of the countermeasures which have been applied to air suspensions on road trains, and certain anecdotal evidence, suggests that the mean axle loads in some air-suspended axle groups could be varying by more than 5 %. Accordingly, this parameter was included in some of the simulations carried out.

5. COMPUTER SIMULATION OF MULTI-COMBINATION VEHICLES

Computer simulation has been carried out in order to:

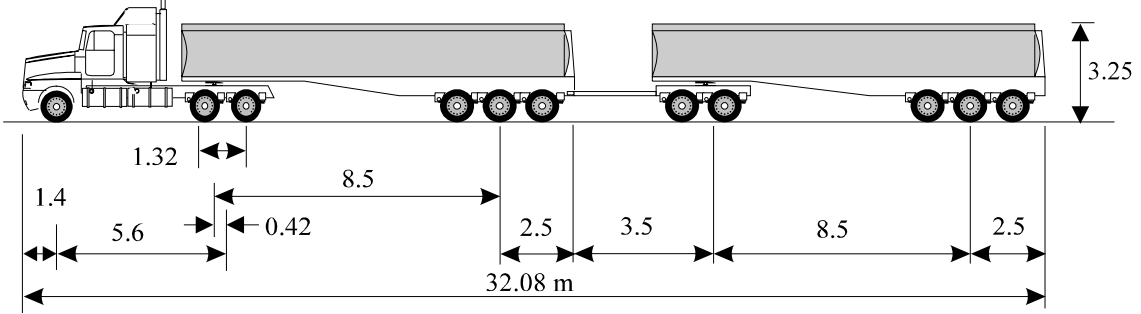
- Provide baseline performance measures against which a range of design variables, modifications and maintenance changes may be judged; these baseline runs also show the effects of the most obvious variables in the study: road train configuration (triple versus double), mass-and-COG-height and suspension type (typical air versus typical mechanical)
- Indicate which of the potential range of performance measures are most sensitive to road train variables, and deserve closer investigation in this study
- Indicate which performance measures may be sensitive to road conditions, and therefore may not provide a fair vehicle performance assessment under road train operating conditions
- Indicate which design variables, modifications and maintenance changes have the greatest effect on road train performance.

The simulation models, baseline vehicles and performance measures are described in Annex A. Figures 7 & 8 illustrate the baseline double and triple road trains simulated, their dimensions and axle weights. These baseline vehicles were selected in consultation with the Project Management Team Advisory Committee and represent the range of current general road train configurations, covering vehicles with regulation mass and moderate centre-of-gravity (COG) height through to higher (concessional) mass and high COG height. These vehicle combinations were all simulated with generic air suspension and generic mechanical suspension in the following suspension layouts:

- Air suspension on prime mover (with the exception of the steering axle) and trailers, and mechanical suspension on dollies
- Mechanical suspension throughout with the exception of air suspension on the prime mover drive axles
- Air suspension throughout (with the exception of the prime mover steering axle)
- Mechanical suspension throughout
- Mechanical suspension on the prime mover drive axles and on the dollies, and air suspension on the trailers.

The generic suspension parameters were selected taking into account the ranges of air and mechanical suspension parameters (covering all heavy vehicles) published in the literature, as well as types of suspension which tend to be selected for road train use. Generally speaking, the parameters selected for the generic suspensions were in the sector of mid-range to “better” performance, as compared to the known parameter ranges in the literature.

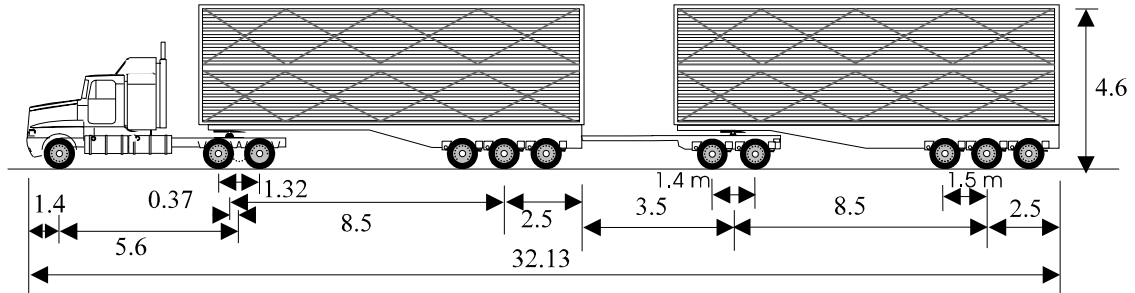
Baseline (Tanker) Double Roadtrain



Axle Loads (t) : GCM 79.0 t

6.0 16.5 20.0 16.5 20.0

Baseline (Stock Crate) Double Roadtrain



Axle Loads: GCM = 89.5 t

6.0 18.5 23.0 18.5 23.0

Figure 7 Baseline double road train combinations

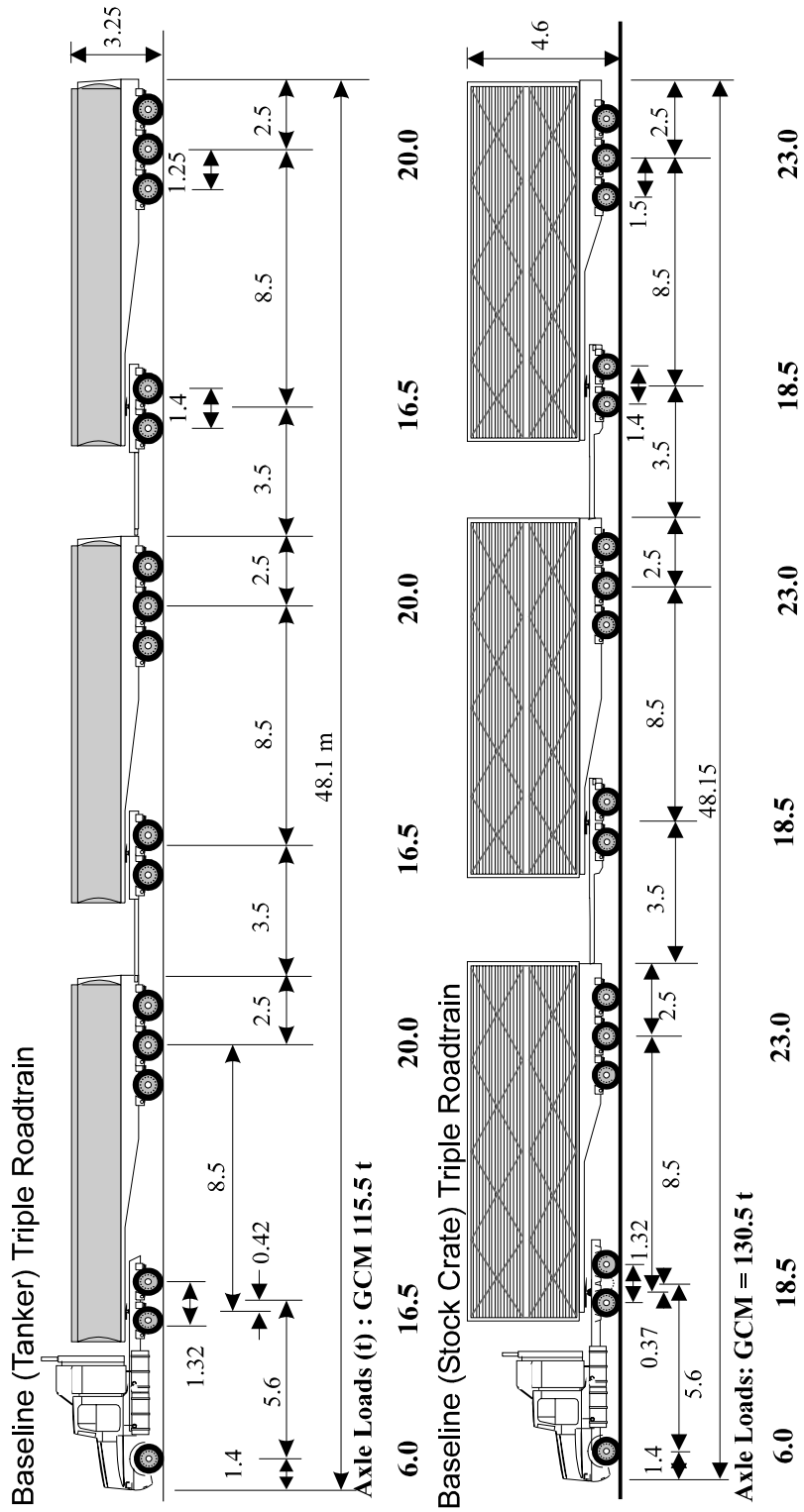


Figure 8 Baseline triple road train combinations

Existing RATED simulation models were modified to include the following real-world road train effects which are potentially vital in this study:

- Lane-change manoeuvres were carried out on rough roads as well as the standard smooth road
- Front axle bump steer was included in the models
- Poor load sharing between axles in axle groups (caused by differing air pressures from axle to axle for air suspensions) was included in the models
- Differing spring rates side to side for drive axle air suspensions (caused by differing air pressures side to side) was included in the models.

In the case of rough roads for the lane-change manoeuvres, the roughness level was equivalent to NAASRA Roughness Meter (NRM) 90 counts/km; this is a reasonably rough road, but not at the extreme of deterioration. It is not necessary to model rougher road conditions as drivers would tend to slow down to suit road conditions rougher than 90 counts/km.

Previous measurements of bump steer coefficient (2) indicated values up to 0.02 deg/mm, and this value was used in the simulations. This value is an extreme value in that it is the highest previously reported.

Simulation models are usually run with load-sharing suspension. This means that the mean wheel loads or axle loads are equal, even though dynamic variations occur above and below the mean. In this study, certain simulation runs were carried out with the mean axle loads made unequal to various degrees; this type of inequality could potentially be caused by air system problems, suspension installation problems or variations in trailer fore-aft attitude. The inequality between the axle loads was expressed in terms of the Load Skew Coefficient (LSC), given by:

$$\text{LSC} = \frac{(\text{lead axle mean load} - \text{rear axle mean load})}{(\text{lead axle mean load} + \text{rear axle mean load})} \quad - (3)$$

and this was varied from a value of + 0.5 through – 0.5.

Previous measurements of air bag pressures in certain drive axle suspensions have shown significant variations from side to side. Taking into account the compensating effect of mechanical anti-roll devices, it has been estimated that, when air pressures are significantly different from one side to the other, the total spring rate could vary by 10 % from one side of the prime mover to the other, and this has been incorporated in the simulation models.

5.1 Baseline Performance Measures

The results of the baseline simulations are given in full in Annex B.

Static Roll Stability (SRS) is strongly affected by the combination of COG height and mass: the stock vehicles have SRS well below the currently proposed (16) minimum PBS value of 0.35 g while the tankers are well in excess of 0.40 g. The suspension type has a lesser but significant effect, with air being approximately 10 % less stable than mechanical. It should be noted that the “typical” suspension parameters used in the baseline simulations were mid-range and larger performance variations could occur between actual examples of air and mechanical suspensions.

In the lane-change manoeuvre, the strongest effect is configuration type (triple versus double). Even for moderate mass and COG height, rearward amplification increases from around 2.5 for the double to 4.0 for the triple; at high mass and COG, the triple cannot complete the manoeuvre without “rolling over”. Similarly strong effects of mass and COG height are evident for high-speed dynamic offtracking (HSDOT): for moderate mass and COG height, HSDOT increases from around 450 mm for the double to 1070 mm for the triple.

Mass and COG height increase rearward amplification by 11 % for the double. The air suspension produces 14 % higher rearward amplification than the mechanical suspension in the case of the triple.

Mass and COG height increase HSDOT by 33 % for the double. The air suspension produces 18 % higher HSDOT than the mechanical suspension in the case of the triple.

High-speed offtracking (HSOT) shows trends reasonably similar to those of the HSDOT measure.

Of the trailing fidelity measures, the 95th%ile rear movement measure provides the most useful results and the mass/COG effect for the triple is 51 % while the suspension effect for the triple is 37 %.

The yaw damping measure provides the best overall comparison of the baseline vehicles, with the following pertinent observations:

- Yaw damping of the triple is approximately 20 % less for the tanker and is *only one third* for higher mass and COG (stock)
- Higher mass and COG (stock) in triples produces yaw damping below the minimum recommended PBS value of 15 %
- For the higher mass and COG trailers, the triple has less than one third the damping of the double
 - With high mass and COG, air suspension produces less than half the damping of the mechanical suspension.

Figure 9 shows typical results for the frequency sweep (transfer function gain between the lateral acceleration at the prime mover and that at the rear trailer). These curves show that the “yaw-roll mode” of the triple stock road train has a resonance in the range 0.25 – 0.5 Hz, which falls within the normal steering frequency range.

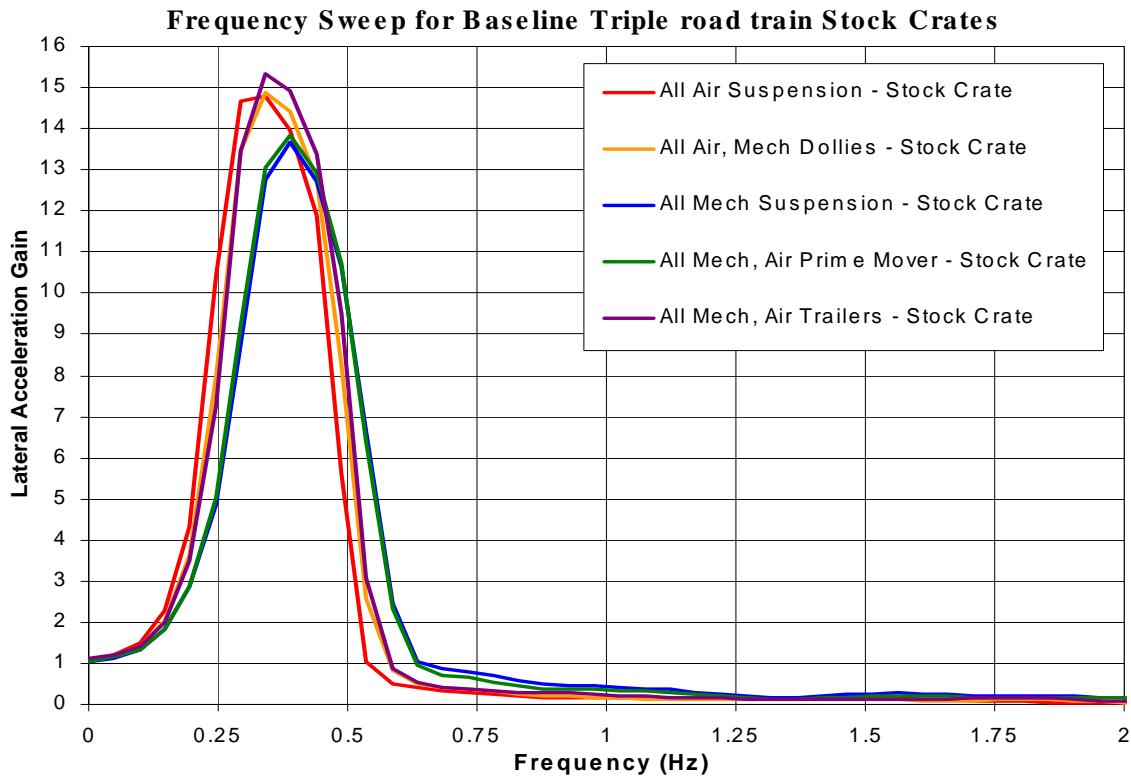


Figure 9 Lateral acceleration gain vs frequency for baseline triple stock road trains

The frequency sweep measures, given in full in Annex B, showed that:

- The peak gain of the triple is more than twice that of the double; dominant frequency is not significantly different between triple and double
- The dominant frequency is strongly affected by COG height and mass (0.3 - 0.4 Hz for high mass and COG versus 0.5 Hz for the tanker); the fact that the gain is highly sensitive to frequency means that the high COG and mass road train will have higher much higher rearward amplification at normal steering frequencies (around 0.25 Hz) but not necessarily in the standard lane-change manoeuvre (0.4 Hz))
- Suspension type (air versus mechanical) mainly affects the dominant frequency; air suspension on the trailers reduces the dominant frequency by up to 0.1 Hz (or approximately 20 %)
- At normal steering frequencies (0.25 Hz): triples have gains generally more than twice those of doubles, high COG and mass produce more than double the gain and air suspension on trailers approximately doubles the gain for high COG and mass only; the nett effect on triples is that air suspension combined with high COG/mass produces three times the gain at normal steering frequencies
- At emergency steering frequencies (0.6 Hz): high COG and mass produce low to moderate gain (because the dominant frequency is relatively low); for the tanker, the triple has approximately twice the gain of the double; trailer air suspension *reduces* gain by 20 % for the tanker and *reduces* gain by a factor of five or more for high COG and mass.

The handling of the prime mover is affected by the mass and COG height and, to a limited extent, by the suspension. The strongest effect is mass and COH height: for the higher mass and COG height case, the transition from understeer to oversteer occurs at a lateral acceleration of 0.18 - 0.22 g, compared to 0.25 – 0.30 g for the tankers. Regardless of the generic suspension type, the higher mass and COG height produces oversteering at a relatively low lateral acceleration.

To summarise the key findings of the baseline simulations:

- Triples perform significantly worse than doubles; this is apparent in almost all measures
- High mass and COG height significantly degrade performance; this is particularly apparent in the lane-change, yaw damping and trailing fidelity measures
- Generic air suspension leads to worse performance than generic mechanical suspension; this is particularly apparent in the yaw damping and trailing fidelity measures
- High mass and COG in triples leads to poor yaw damping and this is halved with air suspension relative to mechanical suspension.

5.2 Initial Investigation of Real-World Road Train Variables

Included in Annex B are the results from simulation models specifically set up to quantify the effects of issues raised by road train operators, and not previously included in simulation models..

Many of the PBS measures are simulated on perfectly smooth roads. To gain some appreciation of the effect of road roughness on dynamic performance measures, the lane-change manoeuvre was simulated on a surface with road roughness level 90 NRM. The following results were obtained: the key lane-change measures (rearward amplification and HSDOT) changed significantly (by up to 17 %), generally increased (ie. worse performance) and changed by different amounts depending on the suspension type (air suspension was less affected than mechanical suspension).

Unfortunately, even though yaw damping has turned out to be a key measure for this study, it is not possible to obtain accurate yaw damping results on a rough road (because the roughness-induced oscillations are overlaid on the yaw responses in a random manner).

The inclusion of front axle bump steer in the models had some interesting effects:

- Increasing the trailing fidelity measure (95th%ile rear movement) by up to 20 % for air-suspended trailers; the increased lateral movement of the prime mover (with the same steering controller gain) due to bump steer is amplified by the trailers
- Increasing the amount of steering input (at the dominant frequency) by approximately 40 %
- Slightly reducing the yaw damping (on a smooth road), by up to 8 %.

The inclusion of poor load sharing on the trailer axle groups had some interesting effects. In the lane-change manoeuvre:

- On a smooth road, the effect of load sharing was small
- On a rough road, a LSC value of + 0.4 increased HSDOT by 11 % on the trailers, 7 % on dollies and 1 % on the drive axle group (a positive LSC means the load biased to the front of the axle group)
- On a rough road, a LSC value of – 0.4 reduced rearward amplification by 8 % on dollies (a negative LSC means load biased to the rear of the dolly)
- On air-suspended dollies, yaw damping increased by 20 % for a LSC of – 0.4 and reduced by 20 % for a LSC of + 0.4; also the peak lateral acceleration gain increased by 6 % for a LSC of + 0.4 and reduced by 10 % for a LSC of – 0.4.

The inclusion of differing spring rates side to side for the prime mover suspension (by 10 %) had a negligible effect on the lane-change measures, yaw damping and trailing fidelity.

5.3 Key Results from Baseline Simulations

5.3.1 Effects of generic variables

Vehicle configuration is a prime variable in road train performance. In almost all measures, triples perform worse than doubles. While this was to be expected, the magnitude of this performance difference has not been fully appreciated in the past:

- Peak rearward amplification of the triple is more than twice that of the double; in the standard lane-change test, rearward amplification of the triple is almost twice that of the double
- Yaw damping of the higher mass and COG triple is only one third of that of the corresponding double
- Trailing fidelity of the triple is approximately 30 % worse than the double.

Increased mass and COG height, as reflected in the stock road trains simulated, has a powerful effect on rearward amplification gain at normal steering frequency; for the triple, this gain is more than twice as great for higher mass and COG (relative to the moderate mass and COG height represented by the tanker). Mass and COG height have a pervasive effect on rearward amplification gain in that the dominant frequency is also affected significantly: it is reduced so that the peak gain moves closer to the normal steering frequency.

Increased mass and COG height also dramatically affect yaw damping: for the triple, yaw damping under higher mass and COG height is less than one third that for the tanker. Higher mass and GOG height also worsen the trailing fidelity by 50 %.

A further undesirable effect of increased mass and COG height is transition to oversteering of the prime mover at a significantly reduced lateral acceleration relative to the tanker case.

Generic suspension type (air versus mechanical) also has a strong effect, with most performance measures showing significantly worse performance with air suspension, especially on the trailers. This starts with Static Roll Stability (a modest 10 % worse with air suspension) and flows through more strongly for the dynamic measures. The dynamic

effects of the suspension are accentuated for the high mass and COG case: air suspension produces (i) twice the rearward amplification gain at normal steering frequency, (ii) less than half the yaw damping of the mechanical suspension and (iii) approximately 40 % worse trailing fidelity.

The combined effects of these generic variables are nothing short of dramatic:

- Comparing an air-suspended higher mass and COG height triple with a mechanically-suspended tanker *triple*: (i) rearward amplification gain at normal steering frequency increases from 2.8 to 11.0, almost four times higher, (ii) yaw damping is reduced to less than one quarter and (iii) trailing fidelity worsens by approximately 75 %
- Comparing an air-suspended higher mass and COG height triple with a mechanically-suspended tanker *double*: (i) rearward amplification gain at normal steering frequency increases from 1.6 to 11.0, almost seven times higher, (ii) yaw damping is reduced to less than one sixth and (iii) trailing fidelity worsens by more than 100 %.

Note that the above results apply to the generic air and mechanical suspensions used in the baseline simulations; these results would not apply to all air and mechanical suspensions, and this is explored further in Section 5.5.1.

5.3.2 *Effects of Real-World Road Train Variables*

Poor load sharing within axle groups can have a negative effect on road train dynamic performance. This is most marked for the air-suspended dolly, where significant forward bias of the load (three quarters of the tandem group load on the lead axle) causes:

- 20 % reduction in yaw damping in the triple
- 6 % increase in peak rearward amplification gain in the triple.

Elevated levels of prime mover bump steer cause the driver to work harder (40 % more steering movement) and the trailing fidelity worsens by approximately 20 %.

Side-to-side variation in prime mover suspension vertical stiffness (as produced by large side-to-side air bag pressure variations) had a negligible effect on dynamic performance.

Finally, some often-quoted indicators of dynamic stability (eg. rearward amplification) are significantly affected by road roughness; measurements carried out on rough roads increase rearward amplification by approximately 20 % and could therefore incur an approximate 20 % penalty in trying to achieve compliance, compared with tests or simulations carried out on smooth roads. On the other hand, the peak rearward amplification gain can be reduced by approximately 25 % when simulated on a rough road, as compared to a perfectly smooth road.

5.3.3 *Most relevant performance measures*

The baseline computer simulations showed that the most relevant and useful performance measures for the road train issues raised by road train operators are:

- Lateral acceleration gain (frequency sweep) – this locates the peak gain and the frequency at which it occurs; it also provides the gains at normal steering frequency and at emergency steering frequency; this information speaks to the degree of exaggerated response at the rear of the combination to steering input of a particular magnitude and frequency content

- Yaw damping – this speaks to the persistence of trailer yaw motions once they are created and becomes critically low for some road trains and road train variables
- Trailing fidelity (95 th%ile movement) – this speaks to the amount of lateral movement at the rear of the combination when the driver is trying to steer a straight line on a moderately rough road.

These measures also have the characteristic of continuously manifesting themselves in normal travel, without the combination being taken to the limit of its performance capability.

The standard lane-change manoeuvre (with its measures of rearward amplification ratio, HSDOT and Load Transfer Ratio) is less useful for road trains because:

- It refers to one steering frequency only (0.4 Hz), which neither aligns with normal steering or emergency steering, and the rearward amplification gain is *highly sensitive* to small changes in steering frequency
- The worst-performing road trains (and hence those of most interest) completely roll over, even in a reduced-severity “standard” lane-change.

Other important measures, which speak to the limit performance capability of the road train and are relevant in this study, are:

- Static Roll Stability of all units
- The prime mover handling diagram, and in particular the lateral acceleration at which the vehicle undergoes the transition from understeer to oversteer.

5.3.4 Effects of key road train variables

While there is clearly a major inherent difference in performance between doubles and triples, any pre-requisites for the safe and effective performance of air suspension on road trains must be able to deal with triples. If triples are covered, it can be safely assumed that doubles are covered. The baseline simulations have shown no areas of performance where the double would be more of an issue than the triple.

Relative effects of COG height and mass

The baseline simulations showed that mass and COG height, whose effects have been bundled together so far, have a dramatic effect on triple road train performance. Key stock vehicle and tanker vehicle mass and COG parameters are given in Table 4. In order to separate the effects of mass and COG height, simulations of triple general freight trailers with the same mass as the tanker but increased COG height of 2.61 m for the lead unit and 2.66 m for the rear unit were carried out; otherwise, the dimensions of this combination were the same as the tanker and stock road trains. These simulations covered the following performance measures:

- Rearward amplification gain at normal steering frequency
- Yaw damping
- Lateral movement (trailing fidelity)
- Handling diagram.

Table 4 Mass and COG Parameters in Initial Simulations

Unit	Body Type	Axle Group Mass (t)		COG Height (m)
		Forward Group	Rear Group	
lead semi-trailer	tanker	16.5	20.0	2.00
	stock	18.5	23.0	2.61
rear semi-trailer	tanker	16.5	20.0	2.05
	stock	18.5	23.0	2.66

The results for the general freight triple given in Annex B may be compared with the results for the tanker and stock triples; the general freight triple has the same COG height as the stock triple, but lower mass.

When the COG height is increased at the same mass:

- The frequency of the peak rearward amplification gain is reduced significantly, the peak gain increases significantly and the rearward amplification gain at normal steering frequency is increased dramatically
- The yaw damping reduces by between 10 % (for the case with all mechanical suspension except air on the prime mover) and 45 % (for the case with all air suspension)
- The trailing fidelity (95 th%ile movement) is affected to only a modest degree.

By comparison, when both COG height and mass are increased (as discussed previously):

- The rearward amplification gain at normal steering frequency is further increased dramatically
- The yaw damping further reduces by between 32 % (for the case with all mechanical suspension except air on the prime mover) and 50 % (for the case with all air suspension)
- The trailing fidelity (95 th%ile movement) further worsens significantly.

On balance, while both COG height and mass have a strong effect on the key road train performance measures, the effect of mass seems to be slightly the stronger.

Effect of suspension roll stiffness, roll steer and damping

Suspension type is clearly a major factor, especially for the higher mass and COG triples. The suspension parameters used for the air and mechanical suspensions are representative of the mid-range of current performance. Table 5 summarises the key parameters used for the two generic suspensions in this study. Vertical stiffness and roll stiffness values differ markedly between “air” and “mechanical” while differences in roll centre height and roll steer coefficient are more subtle. Annex B shows how the generic suspension parameters selected relate to the range of suspensions available in practice; most values are mid-range

for the particular type of suspension (air or mechanical). The suspension parameters are defined in Section 2.2.

Table 5 Suspension Parameters in Initial Simulations

Axle Group	Suspension Type	Suspension Parameters			
		Vertical Stiffness per axle (N/m)	Total Effective Roll Stiffness per axle (Nm/deg)	Roll Centre Height (m)	Roll Steer Coefficient (deg/deg)
drive axle	air	245,200	11,000	0.65	0.15
	mechanical	2,500,000	26,250	0.65	0.15
dolly	air	250,000	14,250	0.59	0.125
	mechanical	2,500,000	26,250	0.75	0.125
trailer	air	250,000	14,250	0.59	0.125
	mechanical	2,500,000	26,250	0.75	0.125

In order to understand the acceptable range of air suspension parameters, some further simulations were carried out with suspension parameter variations (see Annex B). These additional runs carried out for the stock triple on a rough road showed that:

- Reducing the trailer suspension roll stiffness by 37 % increased the rearward amplification gain at normal steering frequency by 25 %
- Reducing the dolly suspension roll stiffness by 37 % increased the rearward amplification gain at normal steering frequency by approximately 10 %
- Doubling the trailer suspension roll steer coefficient increased the rearward amplification gain at normal steering frequency by 8 %
- Doubling the dolly suspension roll steer coefficient had no effect on the rearward amplification gain at normal steering frequency
- Reducing the trailer suspension damping by 80 % had no effect on the rearward amplification gain at normal steering frequency
- Reducing the dolly suspension damping by 80 % had no effect on the rearward amplification gain at normal steering frequency.

The additional runs carried out to investigate yaw damping on a smooth road showed that:

- Doubling the trailer suspension roll steer coefficient reduced yaw damping by 16 %
- Doubling the dolly suspension roll steer coefficient had little effect on yaw damping

- Reducing the trailer suspension damping by 80 % reduced yaw damping by 9 %
- Reducing the dolly suspension damping by 80 % reduced yaw damping by 5 %.

The additional runs carried out to investigate trailing fidelity showed that:

- Doubling the trailer suspension roll steer coefficient increased lateral movement by 38 %
- Doubling the dolly suspension roll steer coefficient increased lateral movement by 9 %
- Reducing the trailer suspension damping by 80 % increased lateral movement by 1 %
- Reducing the dolly suspension damping by 80 % increased lateral movement by less than 1 %.

5.4 Indicators for Performance Deficiencies with Air Suspension

5.4.1 Deficient yaw dynamics

Simulations carried out have shown clearly that the use of generic air suspension (as compared to generic mechanical suspension) on higher mass, high COG triple road trains causes significant changes in dynamic performance. For such road trains, air suspension produces (i) twice the rearward amplification gain at normal steering frequency, (ii) less than half the yaw damping of the mechanical suspension and (iii) approximately 40 % worse trailing fidelity.

Very poor performance is created when the dominant frequency of the combination's yaw-roll dynamics is reduced to a point nearer the normal steering frequency. This occurs with air suspension on the trailers and dollies; air suspension on the prime mover does not significantly affect this type of behaviour. According to the generic simulations carried out, this performance deficiency – which is partially created by higher mass and COG height – can be avoided with generic mechanical suspension parameters on both the trailers and the dollies. Note that these simulations only included generic air and mechanical suspension, and the effects of air suspension with different parameters are considered in Section 5.5.1.

The same situation applies to yaw damping: undesirably low yaw damping is first initiated by higher mass and COG height and is made significantly worse by generic air suspension on the trailers and dollies. According to the generic simulations carried out, this performance deficiency – which is partially created by higher mass and COG height – can be avoided with generic mechanical suspension parameters on both the trailers and the dollies. Again, these simulations only included generic air and mechanical suspension, and the effects of air suspension with different parameters are considered in Section 5.5.1.

The same pattern is evident for lateral movement (trailing fidelity): increased lateral movement on rough roads is first initiated by higher mass and COG height and is made significantly worse by generic air suspension on the trailers and dollies. According to the generic simulations carried out, this performance deficiency – which is partially created by higher mass and COG height – can be avoided with generic mechanical suspension parameters on both the trailers and the dollies. Again, these simulations only included generic air and mechanical suspension, and the effects of air suspension with different parameters are considered in Section 5.5.1.

5.4.2 Handling problems

While the higher mass and COG height condition causes the prime mover to become oversteering at a lower lateral acceleration, the difference between generic air and mechanical suspensions is not major and was not clear from the generic simulations carried out.

The generic prime mover air suspension simulated is considered to be a fair representation of current worst-case, while the mechanical suspension simulated may under-estimate the performance capability of this type of suspension (with regard to roll steer coefficient)

Accordingly, further handling diagram simulations were carried out for the stock triple with the suspension parameters given in Table 6.

Table 6 Suspension Parameters for Further Handling Simulations (Stock Triple)

Axle Group	Suspension Type	Suspension Parameters			
		Vertical Stiffness per axle (N/m)	Total Effective Roll Stiffness per axle (Nm/deg)	Roll Centre Height (m)	Roll Steer Coefficient (deg/deg)
drive axle	air (worst case)	245,200	3,000	0.65	0.23
	mechanical (best case)	2,500,000	26,250	0.65	0.05

These results (included in Annex B) showed that, while the best case mechanical suspension provided little improvement over the generic mechanical suspension, the worst case air suspension dramatically increased the tendency to oversteering; this is illustrated in Figure 10.

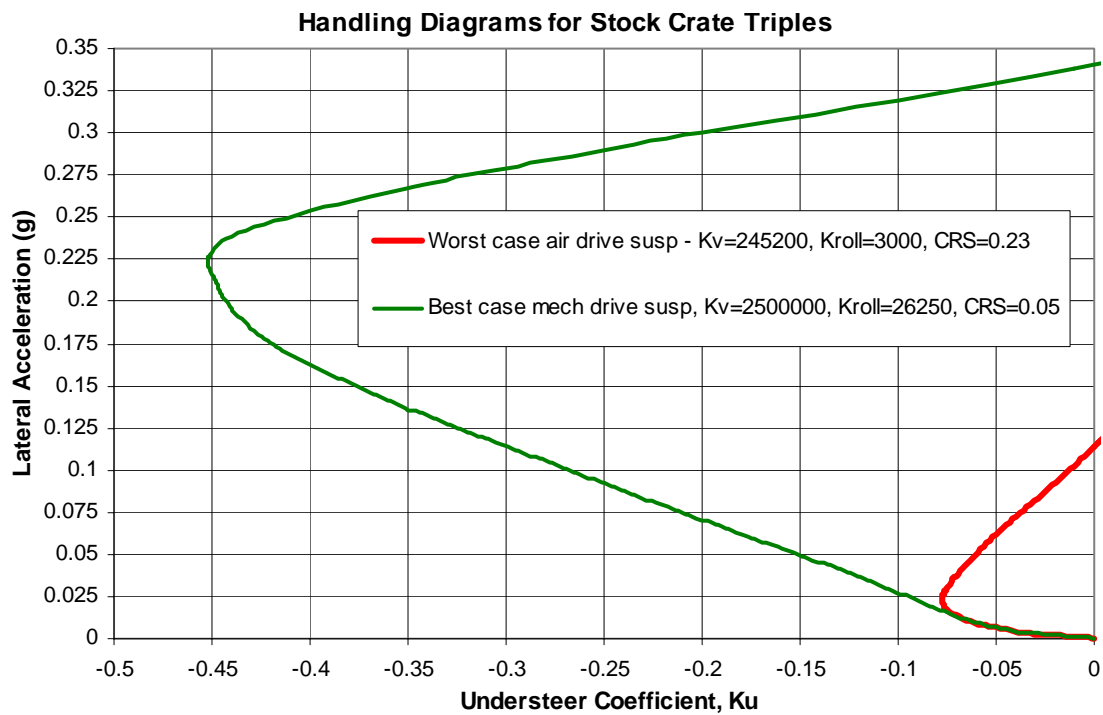


Figure 10 3-Point handling performance diagram for triple stock crates with best and worst case drive axle group suspensions

Prime mover steering axle bump steer also deserves further consideration as a cause of poor yaw dynamics. Further simulations were carried out for the all-air-suspended stock triple, as shown in Table 7. The performance measures evaluated were:

- Rearward amplification gain at normal steering frequency
- Yaw damping
- Lateral movement (trailing fidelity)

Table 7 Parameters for Further Bump Steer Simulations (Stock Triple)

Steer Axle Bump Steer Coefficient (deg/mm)	Load-Skew Coefficient (DLC)	Suspension Parameters (on all air suspensions)			
		Vertical Stiffness per axle (N/m)	Total Effective Roll Stiffness per axle (Nm/deg)	Roll Centre Height (m)	Roll Steer Coefficient (deg/deg)
0.02	0	250,000	9,000	0.59	0.05
		250,000	9,000	0.59	0.20
		250,000	19,000	0.59	0.05
		250,000	19,000	0.59	0.20
	+ 0.5	250,000	9,000	0.59	0.05
		250,000	9,000	0.59	0.20
		250,000	19,000	0.59	0.05
		250,000	19,000	0.59	0.20
0.03	0	250,000	9,000	0.59	0.05
		250,000	9,000	0.59	0.20
		250,000	19,000	0.59	0.05
		250,000	19,000	0.59	0.20
	+ 0.5	250,000	9,000	0.59	0.05
		250,000	9,000	0.59	0.20
		250,000	19,000	0.59	0.05
		250,000	19,000	0.59	0.20

The results (included in Annex B) showed very large variations in peak lateral acceleration gain and in the frequency at which this occurs. However, the value of the bump steer coefficient had relatively little effect on lateral acceleration gain. There is a clear effect of suspension roll stiffness: all other factors being equal, increased roll stiffness increases both the peak gain and the frequency at which it occurs – approximately doubling the roll stiffness increases peak gain by almost 20 % and increases the peak frequency by approximately 20 %. The load skew coefficient and roll steer coefficient also have significant effects of similar magnitude.

Figure 11 shows typical results for the lateral acceleration gain vs frequency curves, as affected by the roll stiffness, roll steer coefficient and load skew coefficient of the air suspensions fitted to all trailer and dolly axles. The air suspension parameters have a dramatic effect on the peak lateral acceleration gain and the frequency at which it occurs.

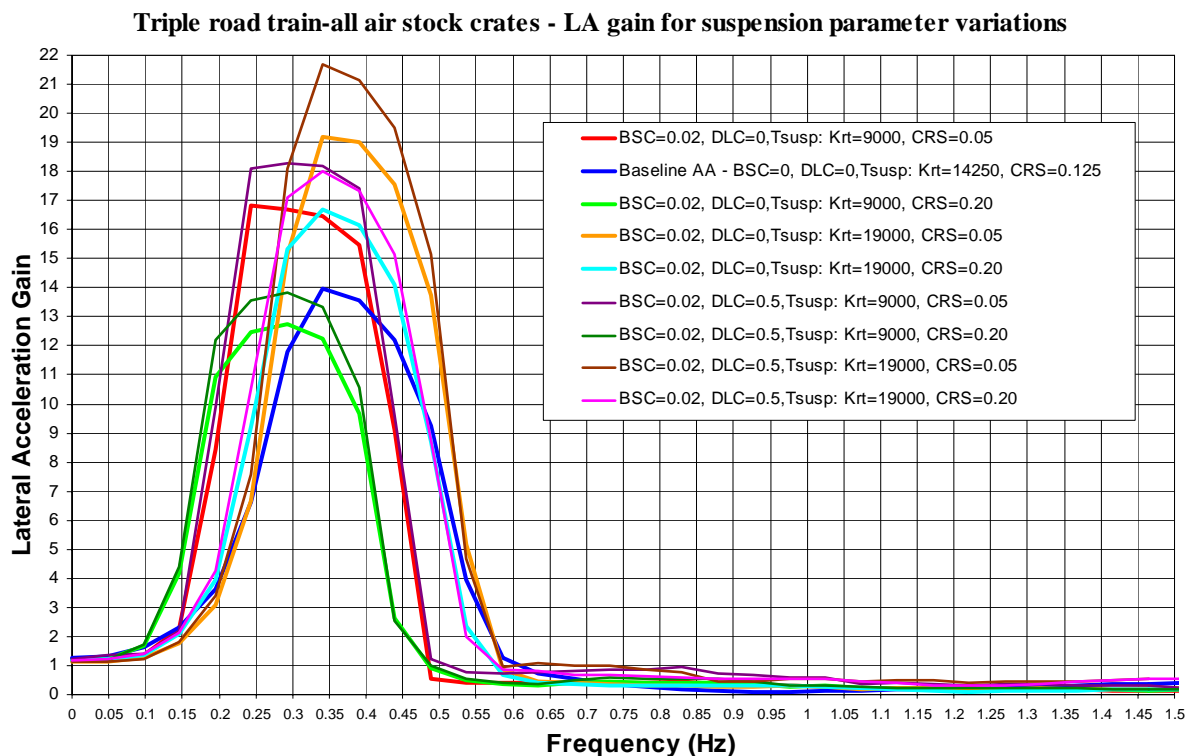


Figure 11 Lateral acceleration gain vs frequency for triple stock road train stock crates with air suspension parameter variations

Considering the lateral acceleration gain at normal steering frequency, the highest values (worst performance) occur for the combination of:

- Low suspension roll stiffness
- Positive axle group load skew coefficient

and lateral acceleration gain at 0.25 Hz increases from 7 – 12 for all other combinations of variables to 12 – 18.

The yaw damping results from the Table 7 parameter variations show that:

- Bump steer coefficient has little effect
- Approximately doubling the roll stiffness increases yaw damping by approximately 65 % - of the variables considered, roll stiffness has the greatest effect
- The combination of roll stiffness and load skew coefficient has a powerful effect: with a positive load skew coefficient (0.5), approximately doubling the roll stiffness increases yaw damping by a factor of four.

The trailing fidelity (95 th %ile movement) results from the Table 7 parameter variations show that:

- Bump steer coefficient has little effect
- Increasing the roll steer coefficient by a factor of four more than doubles lateral movement
- Approximately doubling the roll stiffness reduces lateral movement by almost 40 %
- Load skew coefficient has very little effect on lateral movement

and both roll stiffness and roll steer coefficient need to be controlled in order to control lateral movement.

5.5 Indicators for Resolving Performance Deficiencies with Air Suspension

5.5.1 Deficient yaw dynamics

Air suspensions used on road train trailers and dollies must have minimum performance capabilities in order to avoid high rearward amplification gain at normal steering frequency, low yaw damping and increased lateral movement on rough roads (trailing fidelity).

Not all trailer air suspensions have the generic parameters used for the baseline simulations. In particular, the roll steer coefficient could be significantly lower than 0.125; roll stiffness can also vary significantly while the roll centre height could vary significantly (worse parameters) for underslung suspensions (with roll centre height down to 0.34 m).

Additional yaw dynamics simulations were therefore carried out for the suspension parameters shown in Table 8. In the first set of simulations, only the dolly suspension parameters were varied and the trailer suspensions were generic air. In the second set of simulations, only the trailer suspension parameters were varied and the dolly suspensions were generic air. The performance measures for evaluation were:

- Rearward amplification gain at normal steering frequency
- Yaw damping
- Lateral movement (trailing fidelity)

and the results were intended to provide guidance for minimum standards for trailer and dolly air suspension, if required.

Table 8 Suspension Parameters for Further Yaw Dynamics Simulations (Stock Triple)

Axle Group	Suspension Type	Suspension Parameters			
		Vertical Stiffness per axle (N/m)	Total Effective Roll Stiffness per axle (Nm/deg)	Roll Centre Height (m)	Roll Steer Coefficient (deg/deg)
dolly	air	250,000	9,000	0.59	0.05
		250,000	9,000	0.59	0.20
		250,000	19,000	0.59	0.05
		250,000	19,000	0.59	0.20
trailer	air	250,000	9,000	0.59	0.05
		250,000	9,000	0.34	0.05
		250,000	9,000	0.59	0.20
		250,000	9,000	0.34	0.20
		250,000	19,000	0.59	0.05
		250,000	19,000	0.34	0.05
		250,000	19,000	0.59	0.20
		250,000	19,000	0.34	0.20

The results (included in Annex B) showed that varying the dolly suspension parameters affected the peak lateral acceleration gain; the roll steer coefficient had a greater effect than the roll stiffness. The effect on lateral acceleration gain at normal steering frequency (0.25 Hz) was significant, increasing the gain from approximately 7 to 10 – 12. Higher dolly roll steer coefficient and high roll stiffness both reduced the gain.

Varying the trailer suspension parameters showed that:

- Low roll stiffness reduces the frequency of the peak gain
- Lateral acceleration gain at normal steering frequency is adversely affected by low roll stiffness and low roll centre height; at the low roll stiffness value, this gain is elevated to 13.5 – 16 which represents a large increase
- Roll steer coefficient has a lesser effect on lateral acceleration gain.

The yaw damping results from the Table 8 parameter variations showed no significant trends; however, all yaw damping values were relatively low.

The trailing fidelity (95 th %ile movement) results from the Table 8 parameter variations show that:

- For the dolly, approximately halving the roll stiffness increases lateral movement by approximately 15 %
- For the trailer, the combination of low roll stiffness and low roll centre height has a dramatic effect, increasing lateral movement by approximately 80 %.

Another suspension issue addressed in more detail was load sharing in air-suspended dollies. The baseline simulations showed that yaw dynamics is harmed to some extent by a forward bias of the dolly load distribution. Another dolly issue raised by road train operators is drawbar length. Therefore additional simulations shown in Table 9 were carried out (with all other suspension parameters set to generic air suspension). The performance measures for evaluation were:

- Rearward amplification gain at normal steering frequency
- Yaw damping
- Lateral movement (trailing fidelity)

and the results were intended to provide a guide for minimum standards for air-suspended dollies, if required.

Table 9 Dolly Parameters for Further Yaw Dynamics Simulations (Stock Triple)

Dolly Drawbar Length (m)	Load-Skew Coefficient (LSC) for Dolly	Suspension Parameters			
		Vertical Stiffness per axle (N/m)	Total Effective Roll Stiffness per axle (Nm/deg)	Roll Centre Height (m)	Roll Steer Coefficient (deg/deg)
3.5	0	250,000	9,000	0.59	0.05
		250,000	9,000	0.59	0.20
		250,000	19,000	0.59	0.05
		250,000	19,000	0.59	0.20
	+ 0.5	250,000	9,000	0.59	0.05
		250,000	9,000	0.59	0.20
		250,000	19,000	0.59	0.05
		250,000	19,000	0.59	0.20
4.5	0	250,000	9,000	0.59	0.05
		250,000	9,000	0.59	0.20
		250,000	19,000	0.59	0.05
		250,000	19,000	0.59	0.20
	+ 0.5	250,000	9,000	0.59	0.05
		250,000	9,000	0.59	0.20
		250,000	19,000	0.59	0.05
		250,000	19,000	0.59	0.20

The results (included in Annex B) showed that varying the dolly parameters affected the peak lateral acceleration in certain cases. Firstly, drawbar length had relatively little effect: increasing drawbar length from 3.5 metres to 4.5 metres typically reduces lateral acceleration gain by less than 10 %.

Again, reducing the roll stiffness of the dolly suspension reduces the frequency of the lateral acceleration peak gain. This means that the lateral acceleration gain at normal steering frequency (0.25 Hz) increases greatly, from a value of 7 – 8 (for the generic air stock triple) to values in the range 12 – 17. The presence of a positive load skew

coefficient (0.5) also significantly increases this gain. Increasing the roll steer coefficient on the dolly significantly reduces this gain.

The yaw damping results from the Table 9 parameter variations showed that:

- Increasing the drawbar length has little effect
- Approximately halving the dolly roll stiffness reduces yaw damping by a factor of three
- Dolly roll steer coefficient has little effect on yaw damping.

The trailing fidelity (95 th %ile movement) results from the Table 9 parameter variations show that:

- Increasing the drawbar length has little effect
- Halving the dolly roll stiffness increases lateral movement by almost a factor of two
- Increasing the dolly roll steer coefficient increases lateral movement significantly.

As the dolly air suspension could also have reduced roll centre height (due to the use of underslung suspension), this issue was addressed with the additional simulations shown in Table 10 (with all other suspension parameters set to generic air suspension). The performance measures for evaluation were:

- Rearward amplification gain at normal steering frequency
- Yaw damping
- Lateral movement (trailing fidelity)

and the results were intended to provide further insight for minimum standards for air-suspended dollies, if required.

Table 10 Additional Simulations for Dolly Suspension Roll Centre Height (Stock Triple)

Dolly Drawbar Length (m)	Dolly Load-Skew Coefficient (DLC)	Suspension Parameters			
		Vertical Stiffness per axle (N/m)	Total Effective Roll Stiffness per axle (Nm/deg)	Roll Centre Height (m)	Roll Steer Coefficient (deg/deg)
3.5	0	250,000	9,000	0.59	0.05
		250,000	9,000	0.34	0.05
		250,000	9,000	0.59	0.20
		250,000	9,000	0.34	0.20
		250,000	19,000	0.59	0.05
		250,000	19,000	0.34	0.05
		250,000	19,000	0.59	0.20
		250,000	19,000	0.34	0.20
	+ 0.5	250,000	9,000	0.34	0.05
		250,000	9,000	0.34	0.20
		250,000	19,000	0.34	0.05
		250,000	19,000	0.34	0.20

The results (included in Annex B) showed that, for the dolly alone, the combination of low roll stiffness, low roll centre height and positive low skew coefficient produces particularly adverse performance, with the lateral acceleration gain at normal steering frequency increasing to a value in excess of 18. It is essential to control all of these dolly suspension parameters in order to avoid excessive lateral acceleration gain.

The yaw damping results from the Table 10 dolly parameter variations showed that the combination of low roll stiffness, low roll centre height and positive load skew coefficient produces a dramatic reduction in yaw damping, approaching zero damping. While roll stiffness is the dominant effect, roll centre height and load skew coefficient contribute significantly.

The trailing fidelity (95 th %ile movement) results from the Table 10 dolly parameter variations show that:

- Halving the roll stiffness approximately doubles the lateral movement
- While lowered roll centre height and positive load skew coefficient also have an undesirable effect on lateral movement, their combined effect is small relative to the major effect of roll stiffness.

5.5.2 Prime mover handling problems

The additional simulations in 5.4.2 showed that drive axle air suspension can be significantly worse than drive axle mechanical suspension. A further sensitivity study of prime mover air suspension parameters was therefore carried out to indicate appropriate minimum requirements. The performance assessment was based on the handling diagram, and avoiding transition to oversteering at too low a lateral acceleration. Table 11 shows the simulations carried out for the stock triple road train with generic air suspension throughout (except for the drive axles).

Table 11 Drive Axle Air Suspension Parameters (Stock Triple)

Suspension Parameters			
Vertical Stiffness per axle (N/m)	Total Effective Roll Stiffness per axle (Nm/deg)	Roll Centre Height (m)	Roll Steer Coefficient (deg/deg)
245,200	11,000	0.65	0.05
245,200	11,000	0.65	0.10
245,200	11,000	0.65	0.15
245,200	7,000	0.65	0.05
245,200	7,000	0.65	0.10
245,200	7,000	0.65	0.15
245,200	3,000	0.65	0.05
245,200	3,000	0.65	0.10
245,200	3,000	0.65	0.15

The results (included in Annex B) showed that understeer is promoted by:

- Increased roll stiffness
- Decreased roll steer coefficient.

5.6 Operational Influences

It is important to ensure that potential performance deficiencies are evaluated under reasonable worst case operating conditions. While this has been well covered for mass and COG height, dynamic performance is highly sensitive to vehicle speed and some operators are known to have reduced operating speeds to avoid performance issues. The key measures of yaw dynamics have been evaluated at the following standard speeds:

- Rearward amplification gain (frequency sweep) at 90 km/h
- Yaw damping at 100 km/h
- Trailing fidelity (lateral movement) at 90 km/h.

As road trains operate at nominal maximum speeds of 100 km/h, and in some operating situations are not able to operate any faster than approximately 80 km/h, additional simulations were carried out to:

- Indicate the degree of speed-sensitivity of the key yaw-roll dynamics measures
- Take into account dynamic performance at practical operating speeds
- Ensure that any air suspension performance requirements are sufficient to avoid performance deficiencies at speeds up to 100 km/h.

Two groups of additional simulations were carried out:

- Extended baselines for the triples to indicate the effects of the main generic variables (mass and COG height, and suspension type) at the increased speed of 100 km/h (as yaw damping already covers 100 km/h, additional yaw damping runs were done at 90 km/h)
- Worst case combinations of key variables for the stock triple at the increased speed of 100 km/h.

Table 12 shows the extended baselines (for all triples: tanker, stock and general freight) and Table 13 shows the worst case combinations of variables (for the measures and speeds shown in Table 12).

Table 12 Extended Baselines (Triples) at Expanded Speed Range (up to 100 km/h)

Mass and COG Height Condition	Suspension Type	Test Speed (km/h)		
		Frequency Sweep	Yaw Damping	Trailing Fidelity (95 th %ile)
tanker	air	100	90	100
	mechanical	100	90	100
stock	air	100	90	100
	mechanical	100	90	100

Table 13 Worst Case Variables (Stock Triples) at Expanded Speed Range (100 km/h)

Load-Skew Coefficient (LSC) for Dolly	Suspension Parameters			
	Vertical Stiffness per axle (N/m)	Total Effective Roll Stiffness per axle (Nm/deg)	Roll Centre Height (m)	Roll Steer Coefficient (deg/deg)
0	250,000	9,000	0.59	0.05
	250,000	9,000	0.59	0.20
	250,000	19,000	0.59	0.05
	250,000	19,000	0.59	0.20
+ 0.5	250,000	9,000	0.59	0.05
	250,000	9,000	0.59	0.20
	250,000	19,000	0.59	0.05
	250,000	19,000	0.59	0.20

The results for the expanded baselines (included in Annex B) show that the peak lateral acceleration gain increases with vehicle speed; for the generic air stock triple, the peak gain is approximately 20 % higher at 100 km/h than at 90 km/h. The frequency at which the peak gain occurs is not significantly affected by such a speed increase.

Similarly, the acceleration gain at normal steering frequency increases by approximately 30 % when the speed increases from 90 km/h to 100 km/h.

Yaw damping increases when the speed is reduced from 100 km/h to 90 km/h; in the case of the generic air stock triple, yaw damping increases by 60 % for this speed reduction while the effect on the mechanically-suspended stock triple is much less (approximately 15 %).

Trailing fidelity (95 th %ile movement) is little affected in the speed range 90 – 100 km/h.

The results for the worst-case variables expanded speed range (included in Annex B) showed that the adverse effect of low suspension roll stiffness on lateral acceleration gain is exacerbated by increasing the speed from 90 km/h to 100 km/h. This effect is also reflected in yaw damping decreasing and rear movement increasing with increased speed.

6. MAIN FINDINGS & CONCLUSIONS

Road train dynamic performance deficiencies reported by operators have been investigated in detail using computer simulations specifically modified to address the issues raised. The issues raised by operators are described in Section 4. The dynamic performance simulations carried out are described in Section 5 and drew extensively on the available literature (as reviewed and discussed in Sections 2 and 3), particularly with regard to performance measures which may reflect some of the dynamic issues raised and road train parameters which may affect these issues.

The dynamic performance simulations of Section 5 were carried out in a sequential, targeted manner, in order to:

- Identify areas of potential performance deficiency
- Consider means of controlling such deficiencies (if required).

The study has indicated some major deficiencies in the performance of the largest, heaviest road trains when simulated with suspension properties similar to current air suspensions used on dollies, trailer axles and drive axles. These performance deficiencies have similarities to the problems described by road train operators.

The study has also indicated some means of avoiding these major deficiencies and some of these means appear to concur with certain actions already taken by some road train operators.

The findings and conclusions of the study address several aspects of the identification, measurement, mechanics and regulation of road train dynamic performance, including:

- On-road performance issues confronted by the operator and driver
- Performance measures which relate to these issues
- More detailed practical understanding of the dynamic performance of road train triples
- Key areas of performance deficiency created for practical high-productivity road trains
- Potential means of controlling road train performance, as affected by the dollies and suspensions, to avoid dynamic performance problems with minimum interference to road train operations.
- Potential need for further investigation, possibly involving actual testing.

6.1 Main Issues Identified by Operators and Drivers

6.1.1 Problems encountered

Poor dynamic tracking behaviour - variously described as poor tracking, poor dynamics, swaying, wagging, wandering, leaning, erratic tracking, hanging down and poor feel – was the main problem reported by a number of operators. A related persistent complaint was that it was necessary to reduce speed to overcome the problems of poor dynamics. A further significant complaint was shock absorber performance.

Some operators complain of dangerous behaviour on the road and report accidents which have been caused by poor dynamics. Reported dangerous behaviour includes excessive roll and excessive swaying of trailers.

Some operators also complain of difficulties in learning to drive combinations safely and the dangers of using drivers who are unfamiliar with the vehicles in question.

6.1.2 Interventions by operators

Most of the modifications undertaken by operators were applied to air suspensions. These modifications covered both the prime mover and the trailers and included larger air lines, ride height control valve conversions and shock absorber changes.

Operators have also been forced to make significant attempts to overcome problems with air-suspended dollies. One operator installed an additional ride height control valve on a tandem air dolly so that each axle was controlled independently; this was reported to fix the problem. Another operator reported that it was difficult to fix air-suspended dollies, and another reported that he had converted back from air to mechanically-suspended dollies.

One livestock operator converted four sets of road train trailers from air to mechanical suspension and fixed the problems he was experiencing. The combinations continued to operate at the same weights, due to volumetric loading.

6.1.3 Types of road train involved

Virtually all of the problem combinations were triples, comprising tandem drive prime mover, triaxle trailers and tandem dollies.

All of the vehicles investigated had air suspensions fitted to the trailers. Most of the prime movers (but not all) had air suspension. Some of the dollies had air suspension.

Some operators have tried converting back from air to mechanical suspension; this only occurred on trailers and dollies. None of the prime movers were converted to mechanical suspension.

Trailers involved included::

- Livestock (which combines high mass under volumetric loading, high COG and generally shorter wheelbase) – by far the majority of problem vehicles
- Tipper (which generally has shorter wheelbase)
- Flat-top
- General freight
- Tanker, dry bulk tanker and container.

Most of the dollies involved were air-suspended, and - in terms of problem combinations – the vast majority were air-suspended. As there appear to be relatively few air-suspended dollies in road train service, air-suspended dollies appear to be a significant factor in problem combinations.

6.2 Most Relevant Performance Measures

While the report contains a wide range of performance measures, based on the current Austroads/NRTC PBS Project and on other studies in the literature, road trains are specialised and complex vehicle configurations and require careful evaluation. It is

particularly important to listen to the comments of drivers and operators and to fully consider the role of the driver.

Performance measures also need to be distinguished in that they may relate to the dynamics of the entire combination, or could mainly address the controllability of the prime mover.

The three most relevant “combination” performance measures for this study were found to be:

- Lateral acceleration gain (frequency sweep) – this locates the peak gain and the frequency at which it occurs; it also provides the gain at normal steering frequency; this information speaks to the degree of exaggerated response at the rear of the combination to steering input of a particular magnitude and frequency content – in particular, it quantifies the unwanted exaggerated trailer response at normal steering frequencies which the driver cannot avoid
- Yaw damping – this speaks to the persistence of trailer yaw motions once they are created and becomes critically low (poor performance) for some road trains and road train variables
- Trailing fidelity (95 th%ile movement) – this speaks to the amount of lateral movement at the rear of the combination when the driver is trying to steer a straight line on a moderately rough road.

One “prime mover” performance measure was also found to be important: the handling diagram, and in particular the lateral acceleration at which the transition from understeer to oversteer may occur (see “second point” in Figure 1). Note that, even though the main mechanisms causing oversteering are confined to the prime mover, its onset also depends on characteristics of the lead trailer, with mass and COG height being paramount.

6.3 Dynamic Performance of Road Train Triples

Most of the swaying problems reported by triple road train operators are caused by the yaw-roll dynamic mode of the combination. Any dynamic mode has the following characteristics:

- A natural frequency – a small amount of input (steering) at this frequency causes a large output (swaying at the rear)
- A damping ratio – once the input ceases, how quickly does the swaying die out?
- A gain – how many times larger than the input is the output?
- A phase relationship – if the input (steering) goes to the right, does the swaying motion go to the right at the same time, or with some delay?

The yaw-roll dynamic mode of a triple road train has a very low natural frequency, a low damping ratio, a high gain and tends to be in-phase. Each trailer sways and rolls more than the trailer in front of it. Because the sway increases from each trailer to the next, the lateral acceleration increases and this causes the roll to increase. When the roll increases, tyre vertical loads increase and the tyre side force capacity reduces. This causes the trailer to sway more to develop the required side force. If the suspension allows more roll to occur (low roll stiffness) or geometrically reduces the tyre side force (roll steer), this closed loop of effects is accentuated.

For a triple road train, the natural frequency in yaw (the “plan view” of a series of pendulum-like masses controlled by tyre side forces) is very close to the natural frequency in roll (the view from the rear of each trailer rocking from side to side on its suspension) and therefore the combined “yaw-roll” mode is very powerful.

Crucially, the frequency of the roll mode is reduced by higher mass, increased COG height and lower roll stiffness. The frequency of the yaw mode is reduced by higher mass and suspension roll steer. The frequency of the combined yaw-roll mode is well above the normal steering frequency for most heavy vehicles, but can be reduced sufficiently in triple road trains so that normal steering input produces an abnormally high output (swaying).

The frequency sweep measures, relating lateral acceleration at the rear trailer to that of the prime mover, showed the following critical features:

- The peak gain of the triple is more than twice that of the double; the dominant frequency is not significantly different between triple and double
- The dominant frequency is strongly affected by COG height and mass (0.3 - 0.4 Hz for the stock vehicle with high mass and COG versus 0.5 Hz for the tanker); the fact that the gain is highly sensitive to frequency means that the high COG and mass road train will have much higher rearward amplification at normal steering frequencies (around 0.25 Hz) but not necessarily in the standard lane-change manoeuvre (0.4 Hz)
- Suspension type (generic air versus generic mechanical) mainly affects the dominant frequency; generic air suspension on the trailers reduces the dominant frequency by up to 0.1 Hz (or approximately 20 %)
- At normal steering frequencies (0.25 Hz): triples have gains generally more than twice those of doubles, high COG and mass produce more than double the gain and air suspension on trailers approximately doubles the gain for high COG and mass only; the net effect on triples is that air suspension combined with high COG/mass produces three times the gain at normal steering frequencies.

At least for the generic air suspensions used in the simulations, the following scenario produces a combination with highly exaggerated trailer motions which are unavoidable

from the driver’s perspective:

- Triple road train combination
- Air suspension (generic) throughout
- High COG and mass (as occurs for stock vehicles).

The ability of the combination to damp out trailer oscillations after they have occurred is quantified in the yaw damping measure. The study found that:

- Yaw damping of the triple higher mass and COG (stock) is *only one third* that of the corresponding double
- Higher mass and COG (stock) in triples produces yaw damping below the minimum recommended PBS value of 15 %
- With high mass and COG, generic air suspension produces less than half the damping of the generic mechanical suspension.

Rear movement (trailing fidelity) of the triple on a road of moderate roughness increases by approximately 50 % with higher mass and COG (as for a stock vehicle) and by almost 40 % for generic air suspensions versus generic mechanical suspension.

The handling of the prime mover is affected by the mass and COG height of the lead trailer and, to a limited extent, by the suspension. The strongest effect is mass and COG height: for the higher mass and COG height case, the transition from understeer to oversteer occurs at a lateral acceleration of 0.18 - 0.22 g, compared to 0.25 – 0.30 g for the tankers. Regardless of the generic suspension type, the higher mass and COG height produces oversteering at a relatively low lateral acceleration.

Mass and COG height have been found to be major factors in all four key performance measures; of these, mass is the stronger influence.

Suspension parameters also play a major role in the three combination vehicle measures, and to a lesser extent in prime mover handling. Roll stiffness is the most influential suspension parameter, strongly affecting combination rear response, damping and movement. Roll centre height is also a critical parameter. Roll steer coefficient has a major effect on rear movement. The load distribution within axle groups has an appreciable but generally small effect.

Dollies play a critical role in the dynamic performance of triples and the crucial parameters are: roll stiffness, roll centre height and load distribution (where a forward weight bias degrades performance).

6.4 Performance Deficiencies Indicated

The rear trailer motion characteristics of triple road trains with high mass and COG height (as for stock vehicles) and air suspension (similar to the generic parameters used) appear to be undesirable in that:

- The natural yaw frequency of the combination is close to normal steering frequency, causing highly exaggerated steering response at the rear of the combination
- The damping of the trailer oscillations created is insufficient
- The rear movement, as affected by road roughness, is also exaggerated.

The handling of prime movers with low-roll-stiffness, high-roll-steer air suspension becomes undesirable when connected to trailers with high mass and COG height.

Air-suspended dollies with low roll stiffness and low roll centre height cause triple road train combinations with high mass and COG height (as for stock vehicles) to have undesirable rear trailer motion characteristics.

Deficiencies related to undesirable rear trailer motion characteristics are speed-sensitive and the yaw damping in particular decreases with speed.

6.5 Further Investigation and Improvement of Multi-Combination Handling

The apparent performance deficiencies of multi-combination vehicles identified in this study are potentially serious and justify:

- Further investigation to confirm the study findings, especially in relation to the fact that the current findings are based on computer simulation

- If required, development of means to improve multi-combination vehicle handling.

It is recommended that field testing of appropriate multi-combination vehicles is carried out to confirm the key results of this study. Testing should encompass multi-combinations the handling of which owners and drivers are not satisfied with, as well as multi-combinations with apparently satisfactory handling. Test methods should be suitable for quantifying two basic types of performance deficiency: (i) high-gain, low-frequency yaw-roll dynamics and (ii) tendency to prime mover oversteering. The test plan should also include assessment of the effectiveness of feasible countermeasures for multi-combinations with performance deficiencies and should allow for further validation of the simulation models used in this study.

Test vehicles should concentrate on triple road train configurations. At least one such vehicle with yaw-roll dynamics problems should be tested, and at least one vehicle with oversteering tendency. Testing should include one triple stock road train with air suspension and a similar road train with mechanical suspension, both tested at the same concessional weights.

On-road test methods should be capable of measuring:

- Lateral acceleration gain through the frequency range 0 – 2 Hz
- Yaw damping
- Roll angles and roll gradients of least favoured suspensions (those on the rear trailer and prime mover).

In addition, the following measurements need to be made:

- Quasi-static load sharing and load skew coefficients of least favoured suspensions
- Roll stiffness, roll centre height and roll steer coefficient of suspension types used.

If comparative testing following the above principles confirms problems with (i) the low-frequency yaw-roll mode and/or (ii) prime mover handling, further testing should be carried out to determine the effectiveness of known countermeasures and to provide a basis for guidelines for road train dynamic improvement and for any new vehicle or component performance standards which may be required for road trains. According to the simulations carried out, certain dolly and suspension controls could avoid the high mass/COG triple performance deficiencies indicated in this study and allow the continued use of (complying) air suspension.

Based on the indications of the present study, the following countermeasures may be relevant for problem multi-combinations:

- Dollies with sufficient roll stiffness and roll centre height as well as low load skew coefficient
- Sufficient roll stiffness and roll centre height on trailer suspensions
- Sufficient roll stiffness and roll centre height on prime mover suspensions and sufficiently low roll steer coefficient

and these countermeasures should be considered in the testing, along with any other countermeasures which appear to address the road train dynamics issues identified.

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