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 to100 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 is 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 nett 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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