Comparative performance of innovative quad-trailer combinations

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Abstract:

This paper describes an investigation into the on-road performance of a range of quad-trailer heavy vehicle combinations designed for operation in remote areas of Australia. Vehicle performance was investigated via computer simulation of Performance Based Standards (PBS) measures, which assess various aspects of high and low speed vehicle performance. A set of baseline vehicles was investigated incorporating trailer bodies and load-space dimensions selected to suit the following four commodities: general freight, livestock, quarry product and fuel product. A sensitivity analysis was also conducted, investigating the effects of varying several key vehicle characteristics.

Keywords: Heavy vehicle, road train, performance based standards, PBS, Australia, quad-trailer, innovative combination, high-productivity, computer simulation.

1. Introduction

Large multi-combination vehicles such as road trains operate across remote areas of Australia. These vehicle combinations, which generally comprise a prime move hauling two or three trailers provide safe, efficient and reliable road transport in the Australian outback. In recent years there has been a steady increase in the use of these combinations, which is borne out of the requirement for local operators to meet the demands of Australia's growing road freight task.

Driven by the need for further efficiency and productivity gains, transport operators have sought to develop innovative combinations based around the existing road trains. These innovative vehicles comprise combinations of 'A' and 'B' coupled trailer units for which little operational experience exists. These include AAB-quad, BAA-quad, BAB-quad and ABB-quad combinations.

Presently, access for innovative vehicles is granted by local State road authorities. Regulators in Queensland and the Northern Territory have taken a similar approach in the assessment of innovative combinations, ensuring the on-road dynamic performance of these vehicles meets or exceeds that of a range of existing road train designs. In these assessments, vehicle dynamic performance is evaluated by computer simulation using Performance Based Standards (PBS) measures (National Transport Commission, 2008), coupled with on-road testing and appraisal.

These assessment methods have illustrated that the PBS performance of the innovative vehicles generally exceeds that achieved by conventional road trains (A-doubles and A-triples), and this has resulted in the approval of an increasing number of high productivity multi-combination vehicles. In an effort to encourage industry adoption of better performing vehicles, detailed policies are required which outline the technical requirements and the conditions of their operation. However, such policy documents cannot be drafted until several key concerns are addressed, principally relating to the on-road dynamic performance and behaviour of the innovative vehicles.

To facilitate this, an understanding of the performance of a range of these vehicles is required. A large-scale assessment of multi-combination vehicles which seeks to investigate the difference in dynamic performance between varying vehicle configurations (AAB-quad, BAA-quad, etc.), freight commodity types, suspension types, and axle loading concessions has not previously been conducted. An analysis of the sensitivity of the dynamic performance of the vehicles to changes in vehicle geometry, loading or other characteristics is also required, to allow for the effects of these changes to be understood and managed.

ARRB Group Ltd (ARRB) was engaged by Queensland Transport and Main Roads (TMR) and the Northern Territory Department of Planning and Infrastructure (NTDPI) to complete performance assessments and a sensitivity analysis of a range of innovative combinations with varying payload types via computer simulation using a selection of the PBS assessment measures, to allow a broader understanding of the relationships between key vehicle characteristics, and on-road safety and performance.

2. Assessment methods

Vehicle performance was assessed using computer simulation. ARRB's vehicle simulation models are validated against numerous field test results and are considered to be a suitable representation of the vehicle. Simulations were conducted in accordance with the PBS assessment rules, focussing on the measures specifically designed to address the operational safety of the vehicle in on-road scenarios.

While the research project assessed vehicle performance in all applicable PBS measures, for brevity only some measures are presented and discussed here. These include:

- startability, gradeability, and acceleration capability
- tracking ability on a straight path (TASP)
- static rollover threshold (SRT)
- rearward amplification (RA)

The startability, gradeability and acceleration capability standards measure various aspects of the combined engine and driveline performance of the vehicle. The purpose of these standards is to ensure that the performance of the vehicle is sufficient to allow safe operation on grades which the vehicle is likely to encounter. Startability measures the steepest grade on which a vehicle can begin and maintain forward motion. Gradeability measures the maximum grade on which a vehicle can maintain a constant velocity, and also the maximum speed of the vehicle while ascending a 1% grade. Acceleration capability measures the time it takes for a vehicle to travel a distance of 100 meters, when starting from rest.

The primary purpose of the TASP performance standard is to minimise the safety risk associated with lane width and lateral clearance by ensuring that the vehicle remains within its traffic lane when travelling at highway speeds on straight roads with uneven surfaces (varying roughness and cross-slope). Lower TASP values indicate better vehicle performance, as they imply that vehicles require less lane width during travel.

The static rollover threshold (SRT) measure is used to assess the rollover stability of the vehicle. Rollover stability is arguably the most important performance measure for heavy vehicles because it has been strongly linked to rollover crashes. SRT is the level of lateral acceleration that a vehicle can sustain without rolling over during a turn, and is expressed as a fraction of the acceleration due to gravity in units of 'g'. High values of SRT imply better resistance to rollover.

Rearward Amplification (RA) describes the tendency for the trailing unit(s) of a heavy vehicle combination to experience higher levels of lateral acceleration than the hauling unit during a sudden obstacle avoidance manoeuvre. It is an important safety issue in rapid path-change manoeuvres as it can lead to rear trailer rollover. The ratio of peak lateral acceleration at the rear unit to that at the prime mover steer axle is the RA of the vehicle. Lower values of RA indicate better performance. A better-performing multi-combination will have low RA, as these vehicles will pose a reduced safety risk on the road, and reduce the driver's workload.

3. Subject vehicles

The simulation program encompassed many varying combinations of vehicle configuration, freight commodity types, suspension types, and axle loading concessions. Four vehicle configurations were assessed as outlined below, and shown in Figure 1.

- A-triple (triple road train) – the existing regulation 'as-of-right' vehicle
- AAB-quad (double road train towing a B-double)
- BAB-quad (B-double towing a B-double)
- ABB-quad (semi trailer towing a B-triple).

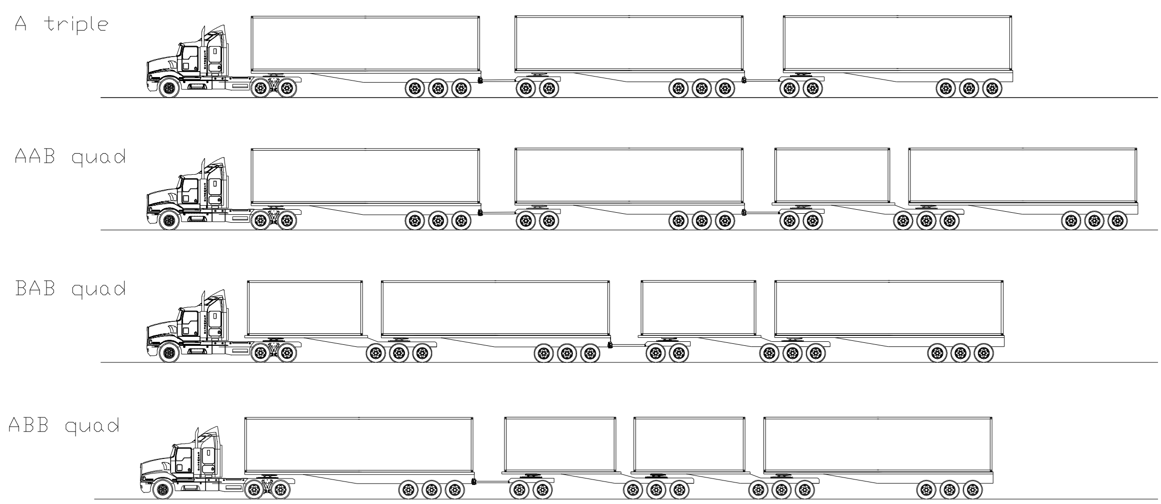

Figure 1 – Examples of subject vehicles

The vehicle configurations were assessed with two variations of prime mover (which varied engine capacity and wheelbase), and trailer bodies and load-space dimensions selected to suit four commodity types; general freight (container freight), livestock, quarry product, and fuel product (tanker).

All vehicles were assessed with axle loads complying with the maximum loads permitted under general mass limits (GML) and higher mass limits (HML) loading schemes. The livestock vehicles were also assessed with axle loads slightly above HML to reflect practical experience with this commodity type in on-road scenarios. Detail on each of these load schemes is summarised in Table 1.

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Table 1: Axle load limits for general and higher mass concessions

Axle group type and position	GML (t)	HML (t)	Livestock (t)
Prime mover steer axle (single)	6.0	6.0	6.0
Prime mover drive axle (tri)	16.5	17.0	18.5
Trailer/dolly axle (tandem)	16.5	17.0	18.5
Trailer/dolly axle (tri)	20.0	22.5	23.5

All combinations were assessed with tandem drive prime movers, tandem axle dollies and triaxle trailers. Some combinations were also assessed with tri-drive prime movers and triaxle dollies. All vehicles were assessed with two generic suspension types: mechanical suspension on all axle groups, and air suspension on all axle groups, with the exception of the steer axle.

Table 2 summarises the combinations of axle group, loading concession and suspension type which were assessed for each vehicle configuration.

Table 2: A-triple, BAB-quad, ABB-quad and AAB-quad assessment matrix

<table>
<tr><th>Commodity</th><th>Prime mover axle group</th><th>Dolly axle group</th><th>Trailer axle group</th><th>Load scheme</th><th>Suspension type</th></tr>
<tr><td rowspan="4">Livestock</td><td rowspan="4">Tandem</td><td rowspan="4">Tandem</td><td rowspan="4">Tri</td><td>GML</td><td>Steel</td></tr>
<tr><td>HML</td><td>Air</td></tr>
<tr><td>Livestock</td><td>Steel</td></tr>
<tr><td>Livestock</td><td>Air</td></tr>
<tr><td rowspan="3">General freight</td><td rowspan="3">Tandem</td><td rowspan="3">Tandem</td><td rowspan="3">Tri</td><td>GML</td><td>Steel</td></tr>
<tr><td>GML</td><td>Air</td></tr>
<tr><td>HML</td><td>Air</td></tr>
<tr><td rowspan="6">Quarry product</td><td rowspan="3">Tandem</td><td rowspan="3">Tandem</td><td rowspan="3">Tri</td><td>GML</td><td>Steel</td></tr>
<tr><td>GML</td><td>Air</td></tr>
<tr><td>HML</td><td>Air</td></tr>
<tr><td rowspan="3">Tri</td><td rowspan="3">Tri</td><td rowspan="3">Tri</td><td>GML</td><td>Steel</td></tr>
<tr><td>GML</td><td>Air</td></tr>
<tr><td>HML</td><td>Air</td></tr>
<tr><td rowspan="6">Fuel product</td><td rowspan="3">Tandem</td><td rowspan="3">Tandem</td><td rowspan="3">Tri</td><td>GML</td><td>Steel</td></tr>
<tr><td>GML</td><td>Air</td></tr>
<tr><td>HML</td><td>Air</td></tr>
<tr><td rowspan="3">Tri</td><td rowspan="3">Tri</td><td rowspan="3">Tri</td><td>GML</td><td>Steel</td></tr>
<tr><td>GML</td><td>Air</td></tr>
<tr><td>HML</td><td>Air</td></tr>
</table>

Variations in axle loading and commodity type dramatically affected vehicle gross combination mass (GCM) and trailer centre of gravity (COG) height, which varied for each combination type as shown in Table 3.

Table 3: Summary of GCM and COG height variations

Vehicle type	GCM mass range (t)	Trailer COG height range (m)
A-triple	115.5 – 141.0	1.97 – 2.91
BAB-quad and ABB-quad	119.0 – 141.0	1.90 – 2.78
AAB-quad	135.5 – 158.0	1.90 – 2.80

The specifications of critical components including suspension and tyre stiffness, trailer tare mass and engine power were conservatively selected from ARRB's experience to yield a 'worst-case' result for vehicle performance. This approach was taken as the purpose of the project was not to determine the performance levels of particular vehicle combinations, but to ascertain the effects of vehicle configuration and other key characteristics of the performance level achieved. It should be noted that the published performance results are expected to indicate a lower level of vehicle performance than would be expected in an on-road scenario.

4. Sensitivity Analysis

A sensitivity analysis was carried out for all vehicles. The sensitivity analysis was completed via the independent application of each of the modifications listed below to the vehicle geometry. Each reference to vehicle geometry is depicted in Figure 2.

- 10% higher trailer centre-of-gravity height
- 10% lower trailer centre-of-gravity height
- 5% shorter 'S' dimension for trailers and dollies
- 10% longer trailer coupling rear overhang.

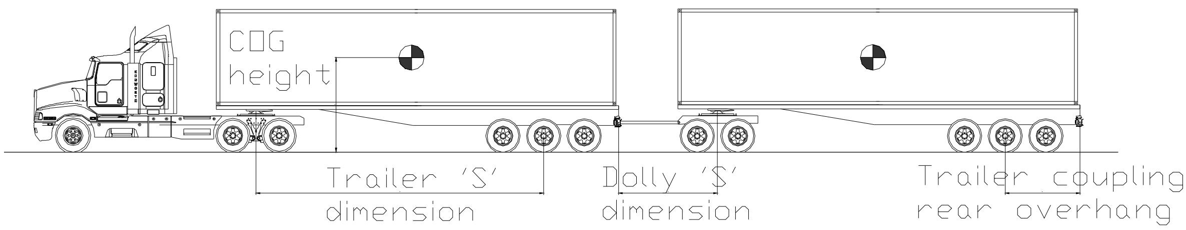

Figure 2 – Modifications to vehicle geometry for sensitivity analysis

Increasing the trailer centre of gravity height is expected to yield worse vehicle performance, primarily in the SRT measure. Similarly, decreasing the trailer centre of gravity height is expected to yield better performance in this measure. Decreasing the S-dimension for trailers and dollies, and increasing the coupling rear overhang for trailer are both expected to yield worse vehicle performance, primarily in the RA and TASP measures.

5. Results

Due to the size of the simulation program, a large volume of results was generated, however only a summary is presented here. The variation of these results for engine and driveline performance are summarised in Table 4. Results which do not meet the PBS Level 4 requirement are highlighted in bold.

Table 4: Summary of driveline results

Performance measure	PBS Level 4 requirement	A-triple	BAB/ABB quad	AAB-quad
Startability	≥ 5%	9% - 11%	9% - 11%	8% - 10%
Maximum grade	≥ 8%	10% - 12%	10% - 12%	9% - 10%
Speed on a 1% grade	≥ 60 km/h	**50.7 km/h – 59.5 km/h**	**50.7 km/h – 59.5 km/h**	**48.4 km/h – 52.1 km/h**
Acceleration capability	≤ 29.0 sec	23.8 s – 24.5 s	23.8 s – 24.5 s	22.9 s – 27.9 s

SRT results achieved by each combination and load condition are summarised in Table 5. Results which do not meet the PBS Level 4 requirement of 0.35 g are highlighted in bold.

Table 5: Summary of SRT results (g)

Axle groups	Loading	A-triple	BAB-quad	ABB-quad	AAB-quad
Tandem	Livestock	**0.31**	**0.30**	**0.30**	**0.30**
	General freight	**0.34**	**0.34**	**0.34**	**0.33**
	Quarry product	0.46	0.48	0.48	0.46
	Fuel	0.37	0.37	0.37	0.37
Triaxle	Quarry product	0.47	0.49	0.48	0.49
	Fuel	0.39	0.39	0.38	0.38

TASP results achieved by each combination and load condition are summarised in Table 6. Results which do not meet the PBS Level 4 requirement of less than 3.30 m are highlighted in bold.

Table 6: Summary of TASP results (m)

Axle groups	Loading	A-triple	BAB-quad	ABB-quad	AAB-quad
Tandem	Livestock	**3.31**	3.03	3.03	**3.33**
	General freight	3.20	3.03	3.03	3.21
	Quarry product	3.05	2.95	2.95	3.08
	Fuel	3.09	2.99	2.99	3.11
Triaxle	Quarry product	3.03	2.95	2.95	3.07
	Fuel	3.06	2.98	2.98	3.12

RA results achieved by each combination and load condition are summarised in Table 7. Results which do not meet the PBS Level 4 requirement of less than 5.7 times the vehicle's SRT are highlighted in bold.

Table 7: Summary of RA results (-)

Axle groups	Loading	A-triple	BAB-quad	ABB-quad	AAB-quad
Tandem	Livestock	**2.92**	1.58	1.23	**2.68**
	General freight	**2.78**	1.31	0.88	**2.10**
	Quarry product	**3.64**	1.64	1.23	**2.64**
	Fuel	**2.67**	1.47	1.11	**2.27**
Triaxle	Quarry product	**3.31**	1.80	1.36	2.70
	Fuel	**2.76**	1.43	1.01	1.97

6. Discussion

Discussion on the results achieved by the subject vehicles in each performance measure is provided in the following sections.

6.1 Engine and driveline performance results

As expected, the engine and driveline performance results were principally influenced by changes in axle loading and GCM, which yielded the range of results achieved by each combination shown in Table 4. The results showed only a small variation in performance between each configuration. As expected, performance in these measures was highest for the A-triple and BAB/ABB-quad vehicles, and lowest for the AAB-quad vehicles. Overall, vehicles achieved performance sufficient to satisfy the requirements of the applicable PBS Level in the startability, gradeability and acceleration capability performance measures, but not in speed on a 1% grade. Results in this area were in the order of 48.4 km/h – 59.5 km/h compared with the standard of (at least) 60 km/h. This means that the typical design of these combinations does not allow them to comply with the PBS Level 4 requirements.

This indicates that for this measure, A-triple and BAB/ABB-quad combinations should be able to achieve a safe level of performance, however some control on the factors that influence performance in this measure (engine and driveline characteristics, GCM) may be required to ensure that vehicles do not fall short of the required performance level. AAB-quad vehicles, limited by their higher GCM, may not be able to achieve the required performance level. The modifications made to vehicles as part of the sensitivity analysis did not have any impact on these results.

6.2 SRT performance results

Interestingly, the SRT performance results showed very little variation between each of the different configurations, however performance varied significantly across commodity types. This indicates that under static conditions, the roll-coupling effect of fifth wheel connections between trailers has little effect on SRT performance, as the varying size and mass of the roll-coupled units across each of the four configurations demonstrated highly similar SRT results. Generally, the lowest level of performance was demonstrated by vehicles with livestock and general freight loading (which typically failed to meet the PBS performance requirement), followed by fuel product and then quarry product, both of which typically met the performance requirement. This trend was reasoned to be a direct result of the lower COG height of these commodity types, and indicates that careful controls on this may be required to avoid adverse performance.

Although not shown in Table 5, vehicles fitted with triaxle groups generally performed slightly better than their tandem-axle equivalents, despite carrying heavier loads. For the selected suspensions, the air suspension generally yielded slightly lower SRT performance than mechanical suspension. The sensitivity study further highlighted the critical effects of COG height on SRT performance; the 10% COG height reduction substantially improved performance, and vice-versa for the 10% COG height increase. Changes in "S" dimensions and longer couplings overhangs had little overall effect on SRT performance.

6.3 TASP performance results

The TASP performance results showed considerable difference between each configuration and load condition. The lowest level of performance was demonstrated by the A-triple and AAB-quad vehicles loaded with livestock and general freight, the livestock vehicles failing to meet the performance requirement. Performance was generally similar between A-triple and AAB-quad vehicles. The BAB/ABB-quad vehicles demonstrated a high level of performance which did not vary substantially across each of the load variations. These trends were reasoned to be due to differences in overall length, and the number and type of articulation points.

In this light, the AAB-quad is at an obvious disadvantage, being the longest, and having an extra articulation point (the AAB-quad has six, while each of the other vehicles have five). Of the remainder, the A-triple has two drawbar-type couplings, while the BAB/ABB-quads have only one each. Interestingly, although trailer order varied between BAB and ABB-quad combinations, the achieved performance result was identical.

Although not shown in Table 6, vehicles fitted with triaxle groups generally performed slightly better than vehicles fitted with tandem axles, and vehicles fitted with air suspension performed slightly worse than those fitted with mechanical suspension, although the difference could be regarded as negligible. In all cases, the reduction of COG height substantially improved TASP performance, while the increase of COG height, coupling rear overhang, and reduction of 'S' dimension slightly degraded TASP performance.

6.4 RA performance results

The conventional A-triples and some of the innovative combinations performed poorly in the PBS lane change (object avoidance) manoeuvre, and in many cases experienced rollover, which meant that comparative results for rearward amplification could not be determined. In order to further analyse vehicle performance the 'load transfer ratio' (LTR) performance measure was introduced. LTR is not presently part of the PBS rules, but remains a useful measure to describe heavy vehicle dynamic performance. During the object avoidance manoeuvre some of the vehicle's trailers experienced an LTR of greater than 1.0, meaning that the wheels on one side of certain trailers may not have been in contact with the road surface, which has the potential to reduce the accuracy of the RA result. Nevertheless, LTR greater than 1.0 is indicative of very poor dynamic performance, as rollover is usually imminent for that level of load transfer. As the intent of the project was to investigate differences in performance between configurations, the severity of the steering input was downgraded and the simulations re-run.

The modified simulations highlighted significant differences in the RA performance achieved by the combinations. The A-triples did not meet the requirements of RA, demonstrating the lowest level of performance. Similar, but slightly improved performance was demonstrated by the AAB-quad, which only met the RA requirements when fitted with triaxles. Both the BAB and the ABB-quad met the PBS RA requirements, and the performance of each was found to be far superior to the A-triple and the AAB-quad in all variations of load and axle number. The positive influence of the roll-coupled 'B-triple' unit situated at the rear of the ABB-quad was clearly illustrated as the RA performance of the ABB-quad was better than the performance of the BAB-quad.

In all cases, the reduction of COG height substantially improved RA performance, while the increase of COG height, coupling rear overhang, and reduction of 'S' dimension slightly degraded RA performance.

7. Conclusions

Overall, the study has highlighted that certain vehicle characteristics have larger influence on performance than others, and these factors can combine to result in vehicle combinations which should be favoured. Although the degree of influence of these characteristics varied across the range of assessment measures, they included GCM, COG height, overall length, trailer configuration, connection type and number of roll-coupled units, and payload type. Careful consideration of these characteristics should take priority when considering vehicle safety performance. These factors were shown to have far greater impact on performance than the suspension types assessed, GML/HML loading, and the remainder of modifications addressed in the sensitivity study.

The highest level of performance was demonstrated by the ABB-quad and BAB-quad combinations, with the ABB-quad also demonstrating superior RA performance to the BAB-quad. Either of these vehicles should be considered superior to the A-triple, as they offer slightly higher productivity, and much higher on-road performance and safety. The A-triple and AAB-quad typically demonstrated the lowest level of performance in all measures; the A-triple hindered by the lack of roll-coupling between trailer units, while the AAB-quad has the additional disadvantages of increased overall length, GCM and the number of articulation points. However, the AAB-quad offers the highest productivity, and it is expected that safe designs may be available which address the identified deficiencies in performance.

The results generated in this project should be used by Australian road authorities in guiding decisions on mass and dimension limits and access arrangements for these types of innovative combinations. The results also have importance for local and international bodies involved in heavy vehicle regulations, as they provide important insight into the impact of vehicle configuration and sensitivities to parameter variation. This can help to direct decision making as to appropriate methods of assessment for other multi-combination vehicles.

The results also indicate the need for the review of the PBS Level 4 performance requirements, as the innovative combinations in most cases demonstrate equal or better performance than 'as-of-right' regulation vehicles (such as A-triples) which currently undertake the same freight task.

8. References

- National Transport Commission 2008, Performance based standards scheme, the standards and vehicle assessment rules, November 2008, National Transport Commission, Melbourne.