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Comparative Dynamic Performance of Two Road Trains

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Abstract

In the search for increasing productivity in the road transport industry, the move to larger and heavier vehicles has brought an associated concern about the on-road safety of heavy vehicles, such as the Road Trains that operate in outback Australia. This paper compares the safety-related dynamic performance of two road trains.

The first road train is a standard A-Triple comprising a tandem-drive prime-mover towing three full-size semi trailers on converter dollies. The second road train, an AB-Quad, is a recent addition to the heavy vehicle fleet. It comprises a tri-drive prime mover towing four trailers, the rear two of which are B-coupled. Both road trains have an overall length of 53.5 m, the A-Triple has a gross combination mass of 115.5 t compared to the AB-Quad's 146 t.

On-road field trials of the two vehicles were conducted, to measure the dynamic response of the vehicles in evasive manoeuvres and the swept width of the vehicle in typical driving. These results were compared to those from computer-based simulations of the vehicles.

Generally, it was found that the AB-Quad had a comparable or better dynamic performance than the A-Triple; despite having more trailers, a greater mass, and more points of articulation.

1. INTRODUCTION

As part of an industry-wide move towards more productive vehicles, the four-trailer road train incorporating a lead trailer from a B-Double (B-Train) has become more prevalent on Australia's remote roads. Offering increased productivity, many operators prefer the vehicle to equivalent-length triple road trains.

Following a concern held by Queensland Department of Main Roads (QDMR) that tri-drive four-trailer road trains had the potential for increased damage to the thin chip seal pavements, ARRB Transport Research (ARRB TR) was commissioned to conduct an investigation into the potential of tri-drive road trains to damage thin chip seal pavements. The investigation into pavement damage is reported in Prem, Ramsay, Potter and Patane (2000).

As part of this investigation, an evaluation of the dynamic performance of the four vehicles examined was conducted for Queensland Transport (QT). This report contains the results of this dynamic performance analysis.

Separate to this, an in-field test program was developed by QT for assessing the dynamic performance of these new heavy vehicle using performance targets based on computer simulation and operating environment. The field test program was designed to assist both industry and government by supporting vehicle innovation and new technological changes and investigating vehicle performance under operating conditions.

Queensland Transport promotes the development of innovative vehicle concepts that improve the productivity of road transport, whilst maintaining or improving road safety. Under these guidelines, Queensland Transport has supported the introduction of a wide range of new vehicle combinations. This new approach to the operation of innovative vehicles involves examination of the dynamic performance of the proposed vehicles, and how they interact with the existing infrastructure and traffic.

2. SIMULATION METHOD

In conducting a dynamic performance analysis, a computer-based model of a vehicle is taken through a range of simulated manoeuvres, and its performance is compared to that of other, similar-sized vehicles.

ARRB TR uses the multi-body dynamics simulation package ADAMS (Mechanical Dynamics Inc., 2000) for its road vehicle modeling and simulation work. ADAMS is suitable for modeling of any general multi-body dynamic mechanical system, and is widely used by the world's major automotive manufacturers. Validation of the computer models used by ARRB TR has been performed by comparing measurements from full-scale tests with predictions from the models (Prem et al, 2000). This current work compares the dynamic performance of a four trailer (AB-Quad) road train to that of a comparable length three-trailer (A-Triple) road train.

Vehicle models were created based on information supplied by QT and by the vehicle and trailer manufacturers. To ensure consistency between vehicle models, the same suspension and tyre characteristics were used on all models. Performance characteristics can then be attributed solely to the vehicle configuration. The AB-Quad vehicle model is shown in Fig. 4.

3. THE VEHICLES

The two vehicles compared in this analysis are described in the next sections, and their dimensions and masses are compared in Table 1. Despite being the same length as the A-Triple, the AB-Quad offers considerable productivity gains through its higher payload, as shown in Table 1.

3.1 Three-Trailer Road Train (A-TRIPLE)

Dimensions are taken from an A-Triple Road Train fuel tanker operated by McIver Transport in Western Queensland. Maximum axle loads for single steer, tandem and tri-axle groups were used, giving a gross combination mass of 115.5 t, and an estimated payload of 75.0 t.

All trailers were modelled as having a sprung mass center-of-gravity (CG) height of 2.2 m, which is considered typical of a fuel tanker. This meets the requirement of having a stability angle of less than 62 degrees, as required by Australian Standard 2809.1 (Standards Australia, 1999). Dimensions and axle group loads are presented in Fig. 1.

3.2 Four-Trailer Road Train (AB-QUAD)

Dimensions are taken from an AB-Quad vehicle also operated by McIver Transport in Western Queensland, supplying petrol from Eromanga to the Jackson oil field. Testing of the dynamics of the vehicle was conducted by Queensland Transport in early 1999, and the computer model of the vehicle was carefully constructed to ensure the dimensions and axle loads matched those of the actual vehicle. Gross combination mass is 146 t, 95 t of which is payload.

This vehicle features a tri-axle drive group, with a 50:25:25 drive torque distribution. That is, half of the applied drive torque is transmitted to the leading drive axle, and the remaining half is split evenly between the center and trailing drive axles.

As with the other vehicle, the trailers were modelled as having a sprung mass CG height of 2.2 m. Vehicle dimensions and axle group loads are presented in Fig. 2, and a picture of the test vehicle is shown in Fig. 3.

4. ANALYSIS METHOD

Using the computer-based models of the vehicles, simulations were conducted for the following four manoeuvres:

4.1 Single Lane Change

The single lane change manoeuvre is a standard test (SAE J2179) which is designed to evaluate the rearward amplification tendencies of multi-articulated heavy vehicles (Society of Automotive Engineers, 1993). The vehicle is driven at a speed of 88 km/h (55 mph) along a straight road section approximately 100 m in length. It then executes a lane change over a distance of 61 m. The lateral displacement of the lane change manoeuvre is 1.46 m, giving a peak lateral acceleration at the steer axle of 0.15 g.

The following measures are recorded during the simulation of the lane change manoeuvre:

4.1.1 Load Transfer Ratio (LTR)

The Load Transfer Ratio (LTR) is the ratio of the difference of the sum of vertical tyre loads between the left and right sides of the vehicle divided by the sum of the vertical tyre loads on both sides of the vehicle. The LTR formula may be applied to individual axles, axle groups, roll-coupled units (such as a trailer and the dolly supporting it), or to the entire vehicle. LTR equals 1 when all the tyres on the right side lose contact with the ground. It equals 0 when the load is the same on the left and right sides, and it equals -1 when all tyres on the left side of the vehicle lose contact with the ground.

Note that, unlike the other measures, LTR is not specifically defined in the SAE standard, since it is difficult to measure experimentally, but can be calculated during simulations.

4.1.2 Trailer Overshoot (TO)

Trailer Overshoot (TO) is due to the rearmost trailer(s) having a greater transient lateral displacement than the nominal width of the lane change manoeuvre. The trailers (usually) do eventually settle down behind the prime mover in its new position, but the requirement of the vehicle to remain within its lane ensures that a limit on the amount of TO is necessary. TO is also referred to as Transient High-Speed Offtracking.

4.1.3 Rearward Amplification (RA)

Rearward Amplification (RA) is the ratio of the maximum lateral acceleration of the CG of the rearmost trailer to the peak lateral acceleration of the steer axle. Since the steer axle acceleration is never a perfect sine wave due to the experimental procedure (or the steering controller during simulations), the root-mean-square (rms) acceleration is multiplied by the square root of two to give an equivalent peak lateral acceleration.

4.2 Pulse Steer Response

As an indication of how quickly yaw or swaying oscillations decay after a transient manoeuvre, the vehicle model is subjected to a short duration steering pulse. Using the test conditions recommended by El Gindy (1995), with the vehicle travelling at a speed of 100 km/h, a steering wheel pulse of 80° (half sine) is applied over a 0.1 s time interval. Using a typical steering ratio of 25:1 this equates to a pulse at the road wheels of 3.2°. No attempt is made to correct the vehicle's heading after the steering pulse is applied. The vehicle's trailers will start heading off course, following the prime mover, but in the transition the yaw rate of the trailers will respond with a decaying oscillation. This type of excitation (a pulse) is commonly used in dynamic systems analysis to establish fundamental dynamic system response characteristics, such as natural frequencies and damping that control how quickly oscillations decay.

The Yaw Damping Coefficient (YDC) is a measure of damping that can be directly related to the response of a simple mass-spring-damper system response:

[Eq. 1] $$YDC = \frac{\delta}{\sqrt{\delta^2 + 4\pi^2}}$$

where δ in the above expression is the logarithmic decrement, which is the logarithm of the ratio of two successive peaks of the response.

Values of YDC range from zero to one. A value of zero indicates there is no damping in the yaw rate response, and oscillations continue indefinitely. A value of one indicates that the response is critically damped, and has only one peak before settling down to its steady state value. It may be interesting to note that for a given initial excitation a critically damped system tends to approach the equilibrium value fastest. Values of YDC decrease with speed, indicating the vehicle becomes less stable and oscillations take longer to decay.

4.3 High-Speed Turn

The high-speed turn examines how the trailers follow the path of the lead unit on highway curves operating at highway speeds. In a low-speed turn the trailers will track towards the inside of the curve. As speed increases, offtracking begins to diminish and actually becomes zero at some speed. Above that speed the trailers may track to the outside of the path of the lead unit, and tyres may strike a kerb (precipitating rollover, for example), drop off the road shoulder, or encroach into oncoming traffic or collide with a vehicle in an adjacent lane.

The test conditions used by Ervin and Guy (1986) are used. The vehicle model is taken around a circular path of radius 393 m at a speed of 100 km/h. The radius taken by the steer axle is subtracted from the radius that the center-line of the end of the rearmost trailer takes, to give a measure known as the High Speed Offtracking (HSOT).

The high-speed turn gives a useful measure of the lane width requirements of the vehicle travelling on curves. A full assessment of lane width requirements would require additional simulations on realistic road surfaces that include the further effects of unevenness and cross-slope, as described in Prem, Ramsay and Fletcher. (2000).

4.4 Low-Speed Turn

When a vehicle makes a low-speed turn, for example at an intersection, the rear of long vehicles will follow a path inside that taken by the front of the vehicle. This is known as low-speed offtracking.

To evaluate the low speed offtracking by simulation, the vehicle model is driven at a speed of 10 km/h with the centre of its steer axle steered to follow a 90° turn of radius 15 m. The path of the center of the rearmost axle group is traced, and the minimum distance relative to the center of the steer path curve is subtracted from the radius of the path taken by the steer axle. This difference is defined as the Low-Speed Offtracking (LSOT). For the same curve, LSOT generally increases with vehicle length, but decreases with the number of articulation points in the vehicle.

5. SIMULATION RESULTS

Simulation results for both vehicles from the four simulation manoeuvres described above are presented in Table 2.

All dynamic performance measures are seen to generally increase with vehicle size. The one exception is Load Transfer Ratio, which is lower for the AB-Quad than for the A-Triple. This is evidence of the benefit of roll-coupling in connecting the rear two trailers of the AB-Quad. Despite the rearmost trailer of the AB-Quad being subjected to higher lateral accelerations than the rearmost trailer of the A-Triple, there is less load transfer during the lane change with the B-coupled unit, and the vehicle is less likely to roll over during such manoeuvres.

Yaw damping is lower for the AB-Quad, due partly to the additional point of articulation, and to the more complicated vibration modes introduced by using different length trailers.

The AB-Quad has a comparable high-speed offtracking to the A-Triple, having a comparable length, greater mass but more tyres with which to resist the lateral forces generated during the turn.

The AB-Quad vehicle was found to be unable to accurately follow the 15 m radius steering path. With 12 drive tyres spread over 3050 mm, the two steer tyres are unable to generate sufficient lateral forces to maintain the prime mover on the prescribed path. The A-Triple uses a tandem drive, spread over 1400 mm, which is considerably easier to turn than a wide-spread tri-drive group. This poor steering responsiveness was not found to exist in any of the higher speed manoeuvres where the steering angles are much smaller.

Investigation of this poor steering responsiveness of tri-axle drive prime movers has been conducted in Canada (Parker, Amlin and Hart, 1998). Their conclusion was that increasing steer axle weight or prime mover wheelbase, or decreasing the drive axle group spread had a beneficial effect on the steering responsiveness of the vehicle. Location of the fifth wheel relative to the centre of the drive group also effects an articulated vehicles' steering responsiveness. This is generally of greater concern in countries where vehicles are likely to experience low friction conditions (ice or snow) than in outback Australia.

Having shorter trailers, and more articulation points, the AB-Quad does not offtrack as much as the A-Triple. Additionally, since the AB-Quad was unable to accurately follow the 15 m radius steer path, the turn radius effectively is larger than for the other vehicle, giving less offtracking during the manoeuvre.

6. FIELD TEST RESULTS

Separate to the simulations, Queensland Transport conducted full-scale tests of the AB-Quad vehicle in the SAE Lane Change manoeuvre, as well as conducting braking and acceleration tests and on-road tests of road space utilisation.

6.1 Lane Change Test

Testing of the AB-Quad was conducted on a controlled road section of the Eromanga-Coonaberry road in South Western Queensland. Vehicle information including axle loads, dimensions, coupling strength ratings, and loading data were recorded and the various components were inspected to ensure that the vehicle was ready for testing. The manufacturer's specifications were examined to ensure that the vehicle and the components met all relevant Australian Design Rules, regulations and specifications. During its normal operation the vehicle carries fuel, but for the tests the road train was loaded with 93,000 litres of water to the normal operating axle weights. The Gross Combination Mass (GCM) was 145.5 t, slightly lower than the maximum of 146 t for this type of vehicle.

The performance characteristics of the AB-Quad were measured using a portable instrumentation module that was designed and developed by Transport Technology Division of QDMR with the assistance of the Vehicle Standards Section of QT. The following instrumentation was fitted to the vehicle:

- A transducer for measuring the distance travelled;
- String potentiometer transducers to measure steer angle;
- Accelerometers for measuring lateral and longitudinal acceleration on the prime mover and on the last trailer;
- String potentiometer transducers for measuring the axle motion relative to the chassis on the rear trailer (intended to partially correct for the component of gravity that the lateral accelerometers sense as the body rolls); and
- A video camera attached to the prime mover facing backward and a video camera attached to the last trailer facing forward.

The objective of this test was to determine the dynamic stability characteristics of the AB-Quad by measuring the forward speed and lateral accelerations through a lane change (obstacle avoidance) course. Rearward Amplification and Trailer Overshoot were determined using the single lane-change manoeuvre detailed in the SAE J2179 standard (Society of Automotive Engineers, 1993).

Painted markers on the road surface defined the layout of the test course and the driver had to complete the manoeuvre at a constant speed without deviating from the test course. The test speed, steering wheel angle, lateral accelerations on the prime-mover and the rear trailer and the body roll angle of the last trailer were recorded. Five successful runs were recorded. Trailer Overshoot was measured by a video camera monitoring the tracking of the rear trailer over white marker lines painted on the road surface as shown in Fig. 5.

6.2 Braking Test

Braking performance was tested against specific performance standards, including Australian Design Rules 35/01 and 38/01 (FORS, 1999). Analysis included the following factors:

- Stopping distance;
- Brake balance and delay;
- Minimum deceleration capacity;
- Braking efficiency;
- The vehicle's braking capability in emergency stops; and
- The response of the brakes at all wheels under various conditions.

Stopping distance, velocity and deceleration were measured as a function of time. In order to determine the relationship between the effects of increased GCM and stopping distance and deceleration rate, the brake tests were carried out at two speeds (35 and 90 km/h) utilising the maximum braking forces available on the vehicle.

In addition, for an in-depth analysis of the brake system, brake tests were also conducted using a mobile roller brake tester. The tester measured the individual axle weights and braking forces on each wheel over a full range of braking effort. Braking efficiencies were calculated using this data.

6.3 Acceleration and Maximum Speed

The objective of the test was to determine the acceleration and maximum speed capabilities of the AB-Quad. These characteristics are relevant when sight distance and clearance times are analysed at intersections and railway crossings. The AB-Quad was operated on a smooth and level road and accelerated at full throttle from a standing position to the maximum "governed" speed, not exceeding 100km/h.

The test vehicle speed and acceleration were measured using the standard instrumentation. Time and speed data were recorded and speed versus time and acceleration versus time plots were generated.

In addition, the on-road performance was also monitored on the entire trip (231 km) that could relate to road width requirements for the operation of the AB-Quad. The vehicle travelled from the Jackson Oil Fields to Eromanga laden and on the return trip unladen. The speed, lateral acceleration and the movements of the rear trailer during these trips were recorded to determine the maximum lateral movement of the rear unit at normal operating speed and to identify any particular road section that could be unsuitable for safe vehicle operation.

6.4 Test Results

At the time of printing, the field data had not been fully analysed. The detailed analysis of results of the field-testing program will potentially assist QDMR and QT to make informed decisions regarding the operation of new innovative freight vehicles, particularly the AB-Quad. These tests would also assist to optimise the performance of this new vehicle and can encourage public acceptance of AB-Quads in Queensland.

7. CONCLUSIONS

From the computer simulation results, the four-trailer (AB-Quad) road train is seen to have generally comparable to or better dynamic performance than an equivalent-length three-trailer (A-Triple) road train. This is confirmed by preliminary results from the field tests. With more trailers, each being shorter, low-speed offtracking and manoeuvrability is improved. High-speed dynamic performance is enhanced by the provision of roll coupling between the rearmost trailers, and a greater number of tyres with which to resist lateral forces.

The method described in this paper for modelling of heavy vehicles and providing a comparative simulation in a range of standardised manoeuvres is useful in providing a performance-based approach to innovative vehicle combinations such as the AB-Quad.

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TABLES AND FIGURES

TABLE 1 – Comparison of Vehicles

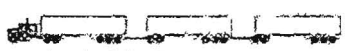
	A-TRIPLE	AB-QUAD
		
Length	53.5 m	53.5 m
GVM / GCM	115.5t	146.0 t
Payload	75.0 t	95.0 t
Tyres	62	86
Driven Tyres	8	12
Power	384 kW (515 hp)	447 kW (600 hp)
Torque	2,516 Nm	2,780 Nm
Power / Weight Ratio	3.32 kW/t	3.06 kW/t

TABLE 2 – Simulation Results

		A-TRIPLE	AB-QUAD
SAE Single Lane Change	Load Transfer Ratio	0.72	0.54
	Rearward Amplification	1.83	2.29
	Trailer Overshoot (m)	0.78	1.01
Pulse Steer	Yaw Damping Coefficient	0.29	0.11
High-Speed Turn	High-Speed Offtracking (m)	0.54	0.54
Low-Speed Turn	Low-Speed Offtracking (m)	8.27	6.30

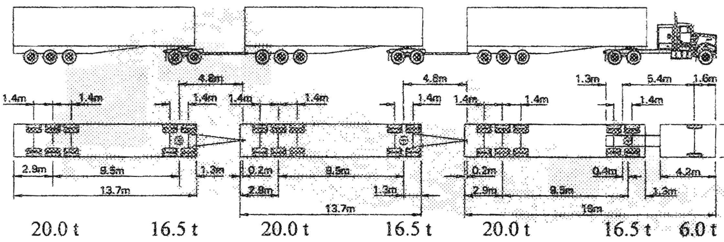


Fig. 1 – Dimensions and axle group loads of the A-Triple road train

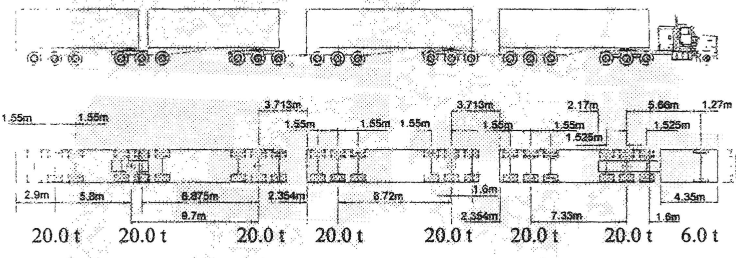


Fig. 2 – Dimensions and axle group loads of the AB-Quad road train

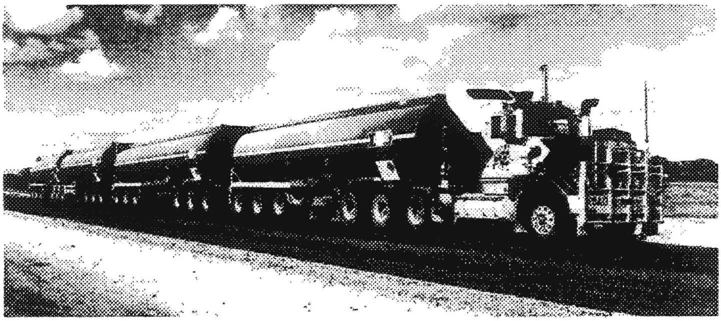


Fig. 3 – The AB-Quad Road Train, as tested by Queensland Transport

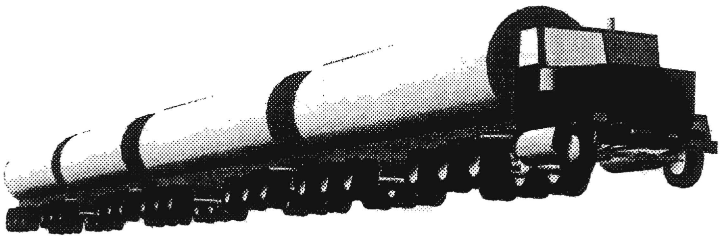


Fig. 4 – The AB-Quad Road Train, as modelled by ARRB Transport Research

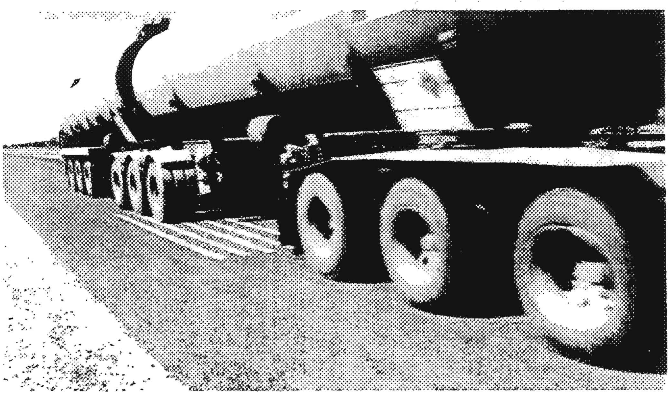


Fig. 5 –Testing of the AB-Quad, lateral displacements measured from lines on road.