TRIAL ASSESSMENT OF STEERABLE AXLE SYSTEM

Peter Sweatman[1], Kerry Atley[2] and John O'Regan[3]

[1]Roaduser Systems P/L
76-80 Vella Drive, Sunshine Victoria 3020 Australia.
[2]Gayat P/L
PO Box 6757, Shepparton Victoria, 3632, Australia.
[3]VicRoads
60 Denmark St Kew Victoria 3101 Australia.

ABSTRACT

This paper describes the results of a 12 month trial of a self-steering triaxle system known as Trackaxle. A tractor-semi-trailer combination incorporating a 15.8 m Trackaxle semi-trailer has been in trial operation in Victoria for some 12 months. This trial proceeded under certain conditions developed by VicRoads including requirements for monitoring and information collection. Trackaxle offers the potential for road freight productivity improvements related to greater access in the road network for semi-trailers and for the use of longer, higher-cube semi-trailers. However, there were some concerns with regard to the safe operation of Trackaxle in traffic, the need for adjustments in driving style and the impact of unexpected trailer tracking behaviour on other road users, including motorists and pedestrians. The review undertaken by Roaduser Systems Pty Ltd included behaviour and interaction in the traffic system, performance assessment against Performance Based Standards, driver behaviour and training, and benefits for improved access, reduced trip times and driver fatigue. The results of the trial are presented and discussed and the potential benefits of Trackaxle for many different transport tasks under different regulatory regimes are discussed.

INTRODUCTION

The continuing drive for improved productivity and safety in road freight operations produces innovative engineering solutions to the problems of managing the intrusion of larger trucks in our road systems. Such innovations are assisted by changes in regulatory approaches, particularly the advent of performance based standards (PBS) as a means of assessing vehicles for permits and eventually as an alternative regulatory system in its own right.

Steerable axles on trailers represent a promising means of improving access of longer vehicles in road systems and operating longer trailers within existing road system constraints. Gayat Pty Ltd of Shepparton, Victoria, Australia have developed an active steering system for semi-trailers. This system is of the "pivotal bogie" type and significantly reduces offtracking in low-speed turns.

VicRoads commissioned Roaduser Systems Pty Ltd to provide an independent evaluation of a 12 month trial of Trackaxle. The Trackaxle active-steering triaxle system has been implemented in a tractor-semi-trailer combination incorporating a 15.8 m trailer and has been in trial operation in Victoria for over 15 months. This trial has proceeded under certain conditions including requirements for monitoring and information collection.

Objectives of the Trackaxle evaluation included:

- Confirming that semi-trailers with a self-steering triaxle group can operate safely and within national PBS
- Assisting industry in evaluating the potential productivity improvements available with self-steering axles

Proceedings 8th International Symposium on Heavy Vehicle Weights and Dimensions
'Loads, Roads and the Information Highway'
Proceedings Produced by: Document Transformation Technologies
14th - 18th March, Johannesburg, South Africa
ISBN Number: 1-920-01730-5
Conference Organised by: Conference Planners

Roaduser's assessment contained the following elements:

- On-road behaviour of the vehicle during the trial, based on direct observation by Roaduser, videos provided by VicRoads, operator and driver reports, interviews and incident reports
- A review of operating conditions based on the outcome of the on-road trials and review of driver training requirements, with specific consideration of the Trackaxle's unusual turning behaviour versus normal on-road practices
- Determination of (i) the ability of the Trackaxle semi-trailer to comply with currently-proposed PBS and (ii) the ability of PBS low-speed turning standards to deal adequately with Trackaxle
- Consideration of the benefits and potential take-up of Trackaxle.

As part of the overall assessment of Trackaxle, certain modifications were introduced by Gayat and tested by Roaduser Systems.

DESCRIPTION OF TRACKAXLE

The steering action of the trailer bogie causes the effective wheelbase of the trailer in low-speed turns to be shortened significantly, reducing the amount of lateral road space occupied by the vehicle combination while turning. Not only does the bogie rotate relative to the trailer, but also two of the three bogie axles steer relative to the bogie. The Trackaxle system is shown in Figure 1.

Figure 1. Trackaxle pivotal bogie.

The Trackaxle concept is a mechanically self-aligning pivotal bogie system that offers hydraulic limitation of its steering action as a function of prime mover articulation angle. The system features a ballrace-mounted subframe to which a set of three standard trailer axles are fitted. The first and last of these axles is mounted on a greasy plate to allow steering that is incremental to the subframe steering angle. The steer angle of these axles is controlled by steering links that are fixed to the trailer chassis. The end result is a system which naturally steers itself back into the straight ahead position when perturbed, as shown in Figure 2.

The system operates on entry into a low-speed turn, where the prime mover pulls the front of the trailer to one side. The subframe tries to continue straight ahead, but is steered in the direction of the prime mover by the linked steering mechanism shown in Figure 2. As the combination straightens on the exit of the turn, the system returns to straight ahead operation. Although the system could theoretically operate with these mechanical entities alone, a skidplate-mounted return assistance mechanism converts prime mover articulation angle into hydraulic feedback which acts to straighten the subframe more quickly. This return assistance mechanism is influenced by (i) the articulation angle of the prime mover relative to the trailer and (ii) the rotation angle of the bogie relative to the trailer.

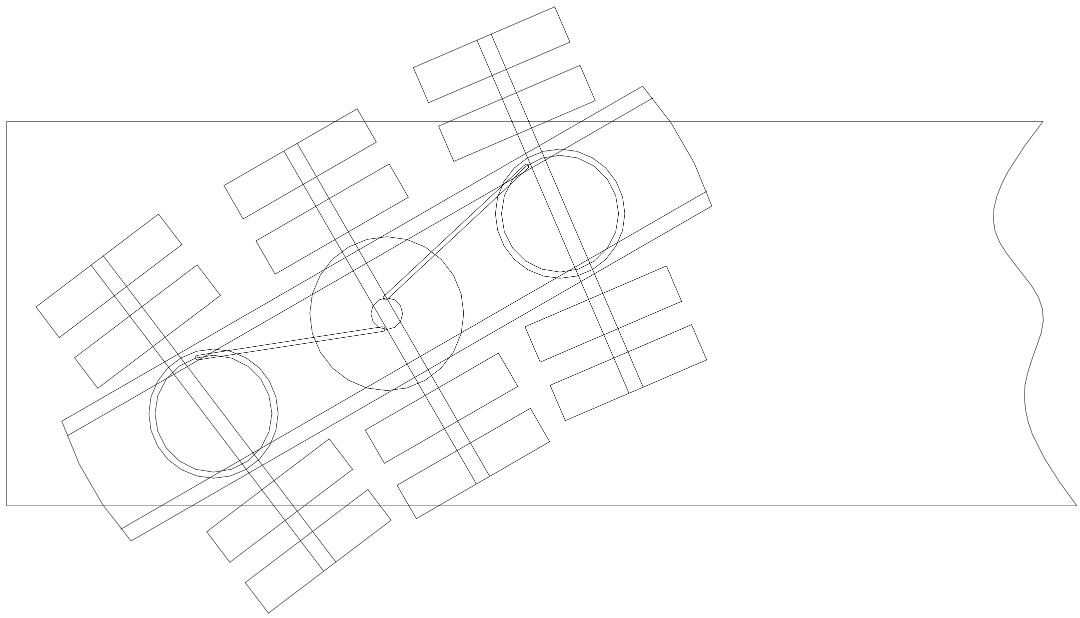

Figure 2. Linked steering mechanism.

The system has a “highway lock” that fixes the subframe in the straight ahead position whenever the prime mover and subframe articulation angles are simultaneously close to alignment; this lock is released when prime mover articulation exceeds a pre-set small angle. The subframe lock is also applied under braking. When the service braking pressure reaches a pre-set level, the subframe lock engages, irrespective of the subframe angle relative to the trailer. When the braking pressure is reduced to a second pre-set level, the subframe lock disengages. The system also incorporates a reversing lock that is activated either by the reversing light circuit or optionally from the cabin; this lock allows reversing with the subframe locked at any angle.

LOW SPEED TURNING TESTS

Roaduser tested the low-speed offtracking performance of the Trackaxle system on Wednesday 9 July 2003 at GMH in Dandenong. The tests were performed in good weather on a dry concrete surface. Tests were performed using a short 4x2 prime mover which had been assigned to the Trackaxle semi-trailer for the on-road trial.

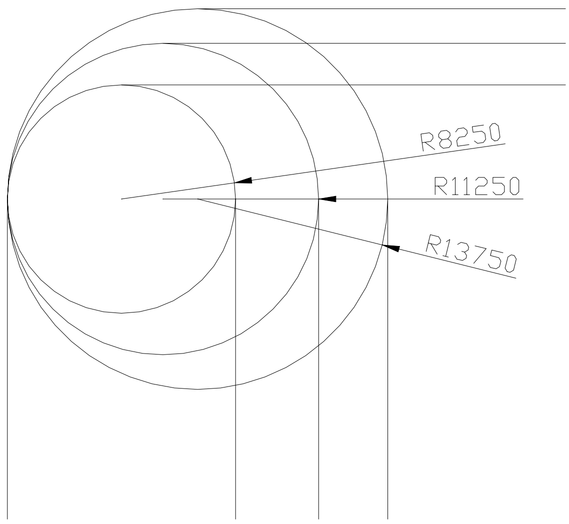

Figure 3. Low speed test manoeuvres (measured to centre of steer axle).

The purpose of the vehicle testing was primarily to verify the simulated PBS Low Speed Offtracking (LSO) and Tail Swing (TS) performance. However, further tests were performed that included 90°, 180° & 360° turns with radii of 13.75 m, 11.25 m and 8.25 m measured to the centre of the steer axle (see Figure 3). LSO and TS of the vehicle were measured during the 90° and 180° manoeuvres using water drippers.

The results of the 90° and 180° manoeuvres are shown in Table 1. Test 2 corresponds to the PBS LSO manoeuvre, and shows that tail swing on entry to and exit from the turn is 250 mm and 300 mm respectively. This is acceptable for PBS requirements.

The 360° turns were performed at radii of 13.75 m and 11.25 m. The rear axle group tracked inside the circle tracked by the prime mover. The swept width of the combination was greater during the 10 m circle.

Table 1. Low speed test results.

Test	Turn Angle (Deg)	Turn Radius (m)	Tail Swing (On Entry) (mm)	Tail Swing (On Exit) (mm)	LSO (m)
1	90	13.75	140	200	5.4
2	90	11.25 (PBS)	250	300	6
3	90	8.25	350	N/A[1]	6.7
4	90	Minimum (approx 6.25)	600	N/A[2]	8.2
5	180	13.75	180	200	5.8
6	180	11.25	250	300	6.6
7[3]	180	8.25	N/A	N/A	N/A

BRAKING STABILITY TESTS

Concerns have been raised about the stability of active steering systems such as Trackaxle under severe braking or braking-in-a-turn scenarios. It is essential that PBS measures are capable of fully testing novel trailer designs in this regard.

The Trackaxle dynamic tests were carried out by Roaduser at Mangalore Airfield on October 21 2003. The weather conditions ranged from showers to heavy rain and therefore provided slippery conditions relevant to the test objectives. The Trackaxle trailer was unladen and was hauled by a Kenworth K104 6x4 COE prime mover. The Kenworth prime mover was fitted with air suspension (Airglide) and was not equipped with ABS.

The vehicle was fitted with the Roaduser instrumentation package and data logger; the prime mover, trailer and subframe were each fitted with lateral acceleration, longitudinal acceleration and yaw rate sensors. The vehicle speed was measured with an ultrasonic Doppler radar.

Special displacement sensors were fitted to measure the following:

- Reversing lock engagement
- Yaw articulation of the trailer relative to the prime mover
- Yaw articulation of the rear steerable subframe relative to the trailer
- Highway lock engagement.

[1] Result was ambiguous due to obstruction in the exit path
[2] Result was ambiguous due to obstruction in the exit path
[3] The subject vehicle failed to correctly track the 8.25m 180° turn path and therefore no results are reported

Test manoeuvres were devised to address the braking issues and to best utilise the available space at Mangalore. In order to carry out repeated stops with the vehicle in a turn of significant lateral acceleration (in excess of 0.15 g) and articulation, a "slalom" test was used, as illustrated in Figure 4.

This test layout has the advantages of:

- Ensuring that the highway locks are disengaged at the commencement of the test
- Turning to both the right and the left
- Variation in surface conditions (compared to turning repeatedly at the same location)
- Efficiency in carrying out multiple stops.

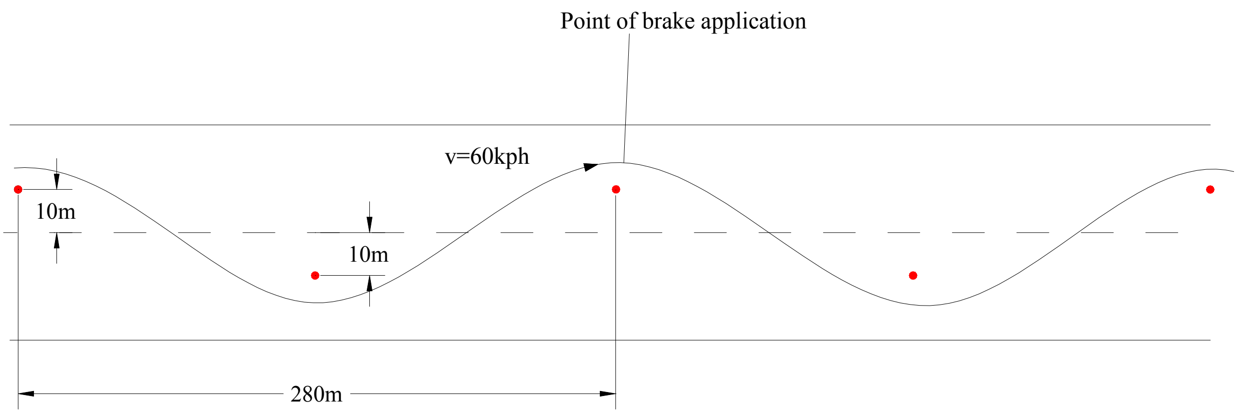

Figure 4. Braking stability test layout.

The brakes were applied at the apex of each turn and the vehicle was braked as hard as possible without causing lock-up of the drive wheels. The vehicle was brought to a halt for each test. The vehicle then accelerated and continued on through the course, braking in the next available turn, provided that a stable initial speed of 60 km/h had been reached. Some straight line tests were also carried out from an initial speed of 60 km/h. The emphasis was on the slalom tests, however, because these were clearly more challenging for the Trackaxle system dynamics.

The main runway at Mangalore provides a flat, level surface of chip seal construction. On the day of the test, the weather was inclement, ranging from showers to heavy rain. The test surface was damp for the earlier tests and wet for the later tests.

The first two test series were carried out with the trailer brakes in a normal state of adjustment. A series of slalom tests were carried out, followed by straight-line tests. The third and fourth test series were carried out with all brakes on the right-hand side of the trailer triaxle bogie inoperative. This meant that all trailer braking was applied on the left hand side of the bogie subframe and created a "worst case" tendency for the subframe to rotate under braking. A series of slalom tests were carried out, followed by straight-line tests.

A fifth test series was carried out with all brakes on the right-hand side of the trailer triaxle bogie inoperative, plus the subframe lock initiation pressure reduced from approximately 35 psi to 25 psi. For the purposes of the test, this provided better protection against lock-up of the drive wheels. A series of slalom tests were carried out. A sixth test series was carried out as for the fifth series, but under conditions of heavy rain with considerable water accumulated on the runway.

Table 2 provides a summary of the test results, showing the key average measures for each test series.

In all tests, the sub-frame locks were activated and de-activated in a positive and appropriate manner. The instrumentation showed that the sub-frame lock activated immediately on braking application and disengaged following the heavy stop only when the brake pressure was reduced to a low level.

Table 2. Braking stability results summary.

Test	Initial Speed (km/h)	Final Speed (km/h)	Prime mover peak deceleration (g)	Prime mover artic. angle (deg)	Sub-frame artic. angle (deg)	Prime mover lateral Acc. (g)	Hwy lock (ON/OFF)
1	62.0	27.0	0.43	11.7	5.7	0.45	ON
2	76.0	17.0	0.38	0.11	4.0	0.04	ON
3	42.7	7.5	0.52	11.5	10.9	0.28	ON
4	60	13	0.47	0.15	5.0	0.05	ON
5	58.7	35.5	0.43	10.3	4.1	0.41	ON
6	59.0	37.6	0.33	9.1	3.5	0.38	ON

Figure 5 shows a typical time history sequence showing:
- Vehicle speed
- Lateral acceleration of prime mover, trailer and sub-frame
- Longitudinal deceleration of prime mover, trailer and sub-frame
- Articulation angle of prime mover (relative to trailer) and of sub-frame (relative to trailer)
- Activation pressure of highway lock and sub-frame lock.

With regard to sub-frame behaviour under braking in a turn, it was found that:
- The initial sub-frame articulation angle was up to approximately 10 degrees
- The prime mover articulation angle was up to approximately 15 degrees
- Following brake application and activation of the sub-frame lock, the sub-frame did not in any case rotate any further than its pre-braking position
- There were no sudden changes in sub-frame articulation either when the brakes were applied, or when they were released.

OBSERVED ON-ROAD BEHAVIOUR

Roaduser's analysis of the on-road behaviour of Trackaxle was predominantly based on observations made by Roaduser during formal testing and "shadowing" of the vehicle on the road, plus discussions with drivers and operators.

The on-road observational component of Roaduser's evaluation was conducted throughout July 2003. The study was conducted by both shadowing the vehicle and accompanying the driver in the prime mover. Overall, the vehicle performed well and appeared to be dynamically stable and there were no significant incidents observed while shadowing the vehicle. However, there were some incidents that occurred during observations from the cabin. Certain incidents relating to the design and/or adjustment of Trackaxle were reported to Vicroads and Gayat and appropriate design modifications were made and tested.

During lane changes, Trackaxle responded well. On some occasions the highway lock released, allowing for some steering input. This did not appear to have a substantial effect on tracking behaviour. Both left and right hand turns could be approached from the inside of a lane with a path similar to that which would be taken by a much shorter rigid vehicle. On some tighter turns Trackaxle seemed slow to return to centre, but did not disturb traffic.

The driver had some difficulty reversing the vehicle at the depots. In yards with more room, the problem was less pronounced.

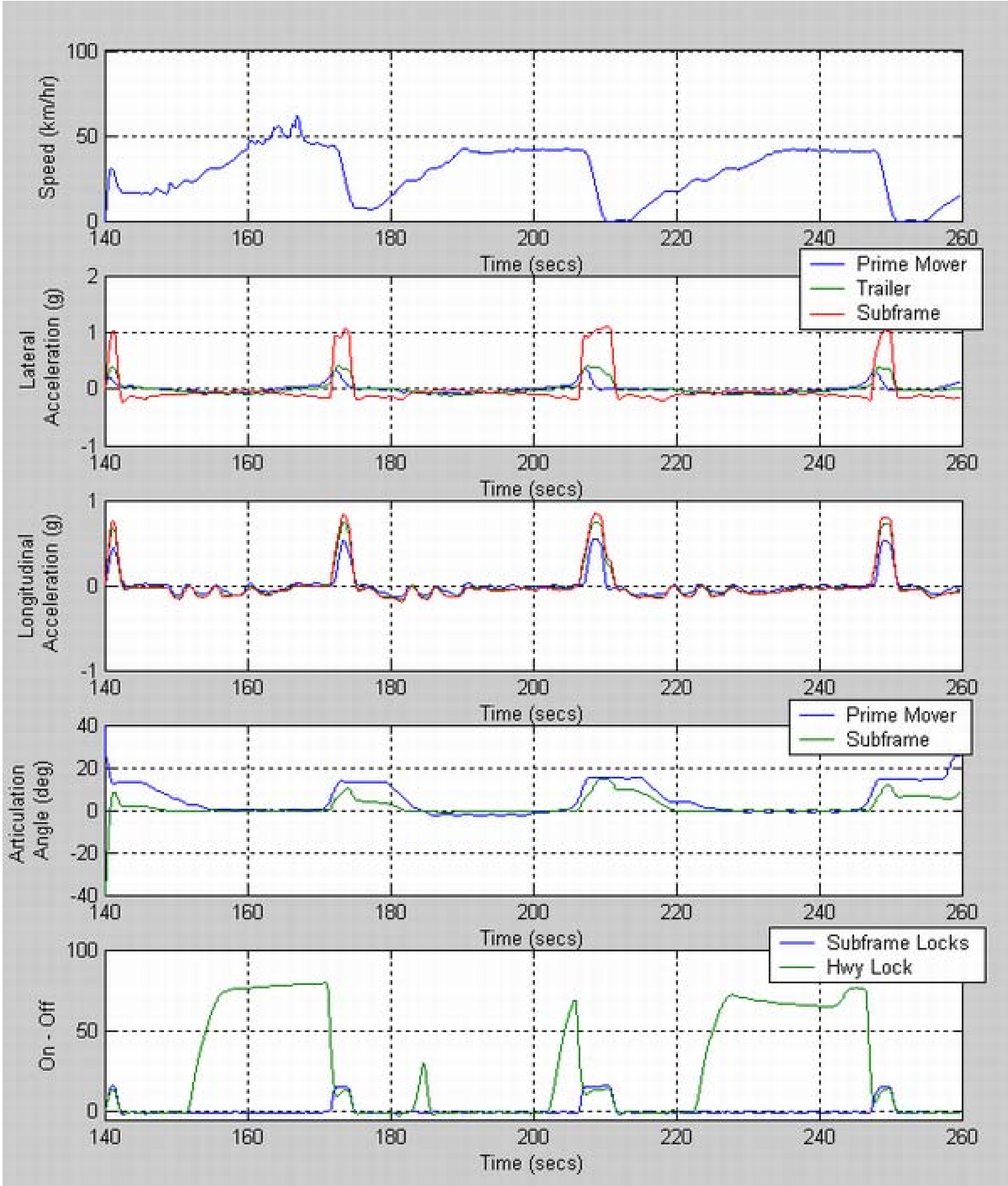

Figure 5. Typical time sequence of vehicle and sub-frame behaviour (test series 5 – left side trailer brakes only).

In heavy traffic, other motorists took very little notice of the subject vehicle and on larger-radius corners were content to overtake on the inside lane.

Because the Trackaxle bogie rotates relative to the trailer, concerns have previously been expressed about the extremities of the bogie protruding outside the confines of the trailer. This behaviour may be clearly seen in Figure 1. Roaduser's observations of on-road behaviour did not find this to be a deficiency.

While the bogie does not remain within the trailer perimeter, it does remain will within the paths tracked by the prime mover and the trailer. This is shown in Figure 6, illustrating the paths of key parts of the combination vehicle during the PBS low-speed 90 degree turn.

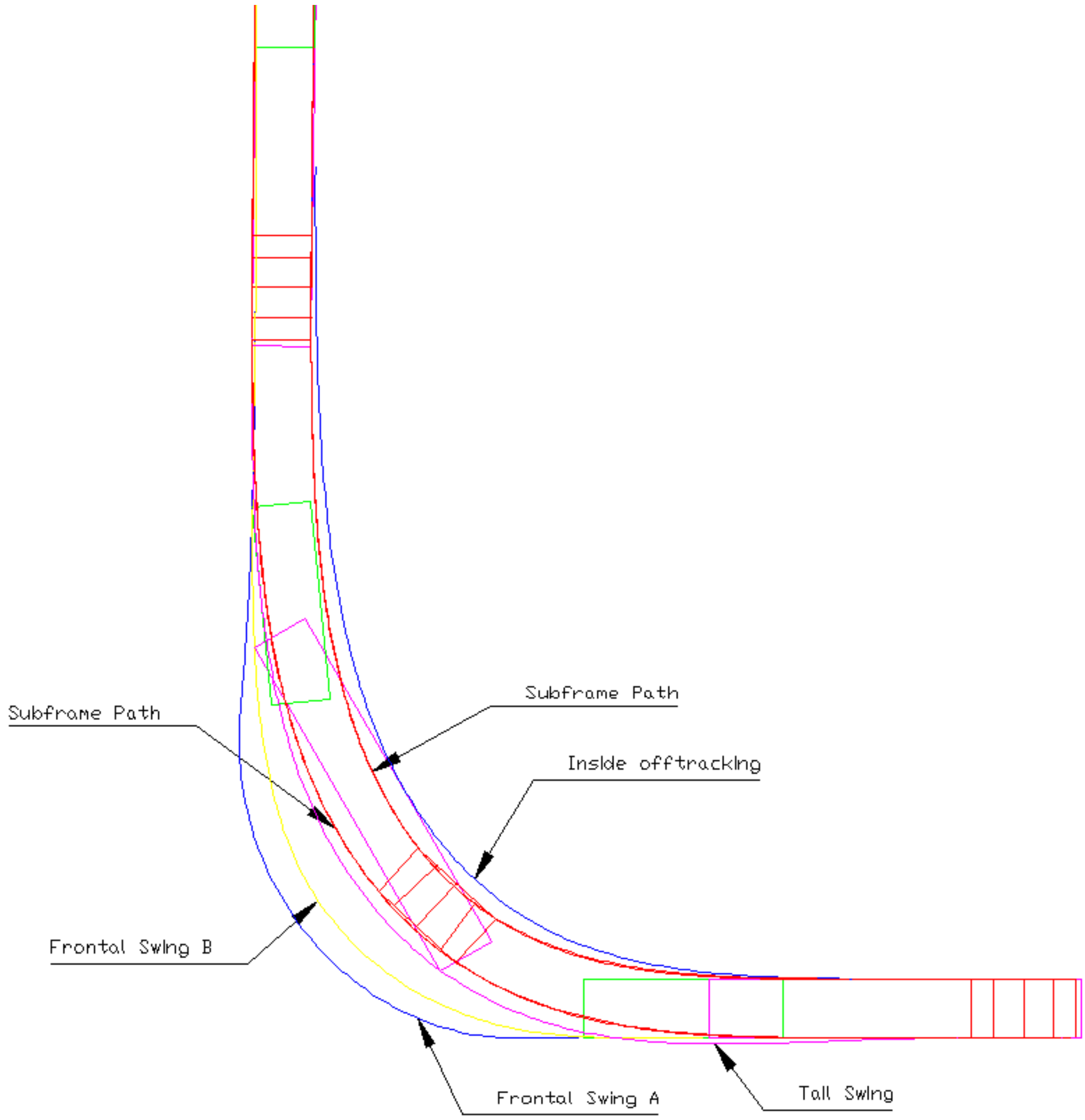

Figure 6. Relative paths of bogie, trailer rear and prime mover.

It is apparent that:

- On the outside of the turn, the front corner of the bogie tracks within the rear corner of the trailer, and well within the prime mover
- On the inside of the turn, the rear corner of the bogie tracks within the mid-section of the trailer.

Accordingly, the tracking behaviour of Trackaxle is considered to be benign with regard to the rotation of the bogie.

Measurements of tail swing in idealised 180 degree turns found that it was within the 300 mm PBS limit. However, on-road observations indicated that tail swing may exceed this in some situations. This could be caused by high lateral acceleration generated in rapid U-turns (not reproduced in the standard low-speed tests) and by cross-fall of the road surface.

The following factors contribute to this issue:

- Other road users, and observers, do not expect to see the trailer “swing out” at all on the exit from the turn, and certainly not to swing out further than the prime mover
- PBS currently allows 300 mm tail swing on the exit of a sedate turn, while conventional semi-trailers would have zero tail swing on the exit
- The PBS test is not intended to cover rapid U-turns.

While education of road users, and adjustment of their expectations and perceptions, may assist with this issue over time, it is likely that an additional PBS measure and associated standard is needed in this area. This type of trailer response is also strongly affected by driver behaviour and appropriate driver training and awareness could make a major contribution.

Appropriate driver training is required for all drivers operating Trackaxle trailers. Due to the specialised and complex nature of the Trackaxle system, and the very significant change in semi-trailer behaviour on the road (both for the driver and for other road users), this training should be provided by an accredited training provider with input from the Trackaxle manufacturer. It is anticipated that a one-day course will be required.

BENEFITS OF TRACKAXLE

The two operators who have used Trackaxle during the trial have reported the following benefits from their perspectives:

- Increased pallet capacity, with associated productivity gains (provided that the pallet mass is not sufficient for the vehicle to gross out – as the Trackaxle has increased tare mass, there could be a payload mass penalty with some types of pallet loading)
- Reduced trip times in urban operation: because the Trackaxle can stay in its lane it is able to bypass queues of trucks at intersections and roundabouts – behaving like a rigid vehicle
- Reduced stress on drivers in urban operations
- Access to certain terminals and docks which would normally be too tight for semis
- Potential to replace rigid trucks with "small" semis on routes involving secondary rural roads with restricted geometry
- Reduced costs and increased life cycle for tyres, wheel bearings, transmission and drive-line plus improvements in fuel consumption
- Reduced maintenance of paved and unpaved surfaces in yards and terminals.

Under a future PBS regulatory regime, Trackaxle offers the potential to:

- Maximise productivity within each vehicle configuration: semis, B-doubles, B-triples, etc
- "Convert upwards" to the next vehicle class; for example, rigids may be converted to semis, semis to B-doubles and B-doubles to B-triples, etc.

Typically, cubic productivity gains of the order 30 % are possible by adopting longer Trackaxle trailers within each vehicle configuration. Conversion upwards, using judiciously placed Trackaxle trailers in combinations, could provide cubic productivity gains of approximately 40 % with one Trackaxle and potentially much greater gains with multiple Trackaxle trailers in combinations. These possibilities have not yet been fully explored.

These productivity gains will be obtained along with benefits for reduced tyre wear and reduced fuel consumption. Roaduser's observations of the Trackaxle steering geometry and associated reductions in tyre scrubbing and drag indicate that these savings will be substantial.

Roaduser also observed that the Trackaxle semi is able to "flow" through urban traffic situations in a manner similar to a rigid vehicle: left and right turns and roundabouts are negotiated easily within one lane, minimising delays and disruption to other traffic. The vehicle is also capable of carrying out U-turns quickly. This means that operators will be able to consider alternative and more direct routes, with potentially significant time savings.

The ability of the Trackaxle semi to eliminate the high level of lateral tyre scrubbing forces, which occurs in all fixed triaxles in low-speed turns, is of some significance to road agencies. While existing measures of pavement wear do not take surface scuffing and lateral deformation into account, the Trackaxle can be expected to reduce certain types of pavement surface wear at intersections.

Trackaxle's contribution to improving vehicle manoeuvring in urban areas is important in reducing the disruption to other traffic caused by semi-trailer movements in urban areas. While this will be a significant benefit to operators in the early stages of Trackaxle take-up, there will eventually be significant community benefits in improved traffic flow and efficiency when there is a significant presence of Trackaxle-style semi-trailers on the Australian road network.

Trackaxle will also make a positive contribution to environmental benefits with reduced fuel consumption in urban operations and reduced tyre usage.

The long-term future will require more efficient, safer and friendlier co-existence of heavy and light vehicles.

The two major avenues to bring this about are:

- Closing the performance gap between large trucks and cars – Trackaxle makes a major contribution in this very desirable long-term outcome
- Providing truck-only facilities – Trackaxle will also assist in this area by reducing the right of way space and cost requirements of such facilities, increasing their feasibility.

Trackaxle therefore fits a long-term vision of a safer and less intrusive road freight transport system.

Inevitably, Trackaxle and similar systems raise the issue of how long semi-trailers may be permitted to become in the future, if fitted with such technology. Currently, semi-trailers world-wide are mainly limited to 13.7 m (45 feet), 14.6 m (48 ft) or 13.6 m (Europe). Trackaxle offers the potential to increase semi-trailer length to 18.3 m (60 ft) with current levels of access to the road system. Alternatively, semi-trailers around 16.15 m (53 ft) could be operated with improved access.

CONCLUSIONS

Trackaxle, and similar active semi-trailer steering systems, provide a dramatic change in the way semi-trailer combinations track and operate in the road and traffic system. They also provide significant productivity benefits, reduce operating costs and reduce environmental impacts of semi-trailer operations. Trackaxle-style systems fit a long-term vision of a safer and less intrusive road freight transport system.

The ability of Trackaxle vehicles to flow better through urban traffic situations significantly benefits transport operators and their customers in terms of:

- Reduced travel times
- Reduced fuel consumption
- Improved access to secondary routes and terminals
- Reduced driver stress.

Provided that Trackaxle-style systems are facilitated via regulatory flexibility (such as PBS), and current incentives continue to apply, their rate of take-up in the national fleet should be sufficient to produce system-wide benefits for road agencies and the community, in terms of:

- Reduced pavement wear at intersections
- Improved efficiency of traffic flow
- Reduced accidents at intersections
- Reduced emissions.

In the long term, active steering systems like Trackaxle will make a major contribution to more efficient, safer and friendlier co-existence between heavy and light vehicles on our roads. Trackaxle fits a long-term vision of a safer and less intrusive road freight transport system.

Currently, semi-trailers world-wide are mainly limited to 13.7 m (45 feet), 14.6 m (48 ft) or 13.6 m (Europe). Trackaxle offers the potential to increase semi-trailer length to 18.3 m (60 ft) with current levels of access to the road system. Alternatively, semi-trailers around 16.15 m (53 ft) could be operated with improved access.

Trackaxle has been tested in low-speed turning manoeuvres and in critical braking situations. Low-speed swept path and manoeuvreability is dramatically improved over conventional semi-trailers, while tail swing behaviour could be an issue in U-turns (not currently covered in PBS). The modified Trackaxle is stable under severe braking in a turn and on slippery surfaces.

Some of the issues raised and addressed with Trackaxle suggest that current PBS measures have not foreseen all the performance controls needed for active steering systems. Firstly, tail swing on exit from a 180 degree turn and stability when braking in a turn and on slippery surfaces need to be fully considered in PBS. Secondly, stability under braking with lateral acceleration needs to be tested: the “slalom” test used here could be considered for this purpose, with the brakes on one side of the trailer disabled.

The performance issues raised, and tests carried out, provide an important lesson for PBS: PBS measures should not be based solely on knowledge and assumptions concerning conventional vehicles. PBS measures should directly address all relevant on-road situations and should not rely on prescriptive technologies as a substitute for direct tests.