Performance-Based Design of an Innovative Truck-Trailer Configuration

Safer and More Efficient Distribution of Liquid Fuel in Australia

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This paper describes the process whereby one of Australia's major fuel distributors recently gained approval to operate an innovative truck-trailer configuration that was needed to overcome some prescriptive truck size and weight limits and to satisfy the company's new policy on the improvement of fleet safety. Using Australia's newly developed performance-based standards for truck size and weight regulation as the design driver, the process began with field testing of the company's safest existing vehicles, went on to the iterative design of an improved concept by vehicle dynamics simulation, and ended with field testing and calibrated computer simulation of a prototype vehicle for certification. While demonstrating a quantum improvement in dynamic stability, the concept also offers a substantial increase in payload capacity. The process was a valuable learning experience for Australia's truck size and weight regulators and performance-based standards practitioners and is expected to pave the way for continued innovation by this company and others.

Australia's National Transport Commission (NTC) has an ongoing responsibility to develop, monitor, and maintain uniform or nationally consistent regulatory and operational reforms relating to road, rail, and intermodal transport.

In May 2001 the Australian Transport Council (ATC) endorsed a policy proposal and principles for the development of a performance-based-standards (PBS) approach to heavy-vehicle regulation, which would act as an alternative regulatory system to the current prescriptive regulations. The PBS system controls vehicle performance outcomes directly rather than indirectly via size and weight regulation. Therefore, greater freedom in vehicle design is possible without compromising safety or infrastructure effect. This will lead to a general improvement in the safety and efficiency of Australia's heavy-vehicle fleet as PBS is taken up by transport operators.

A substantial NTC subproject then developed a set of performance measures and appropriate levels of performance. In March 2004, ATC approved the resultant standards (*1*) as an interim set, pending the submission of the completed PBS package for ATC approval in 2006 and 2007. In the meantime, the interim standards are being used by forward-thinking transport companies to assist in gaining approval for innovative vehicles under each state's unique permit systems.

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While many companies seek to derive efficiency gains from PBS, one company sought a quantum improvement in safety for their fleet, with a substantial efficiency gain at the same time. The company, Shell Direct Pty. Ltd. (a major Australian fuel distributor), was motivated by its Road Transport Taskforce (Hardware Group) to develop a truck-trailer design that would help them achieve the vision of zero rollovers.

With a large portion of its operations being in the State of Queensland, Shell Direct approached the Queensland Department of Transport (Queensland Transport) for endorsement to start a design project using PBS as the design driver, so that the design could go beyond prescriptive size and weight limits to achieve the best safety outcomes. This paper outlines the process undertaken by Shell Direct.

VEHICLE DESIGN PROCESS

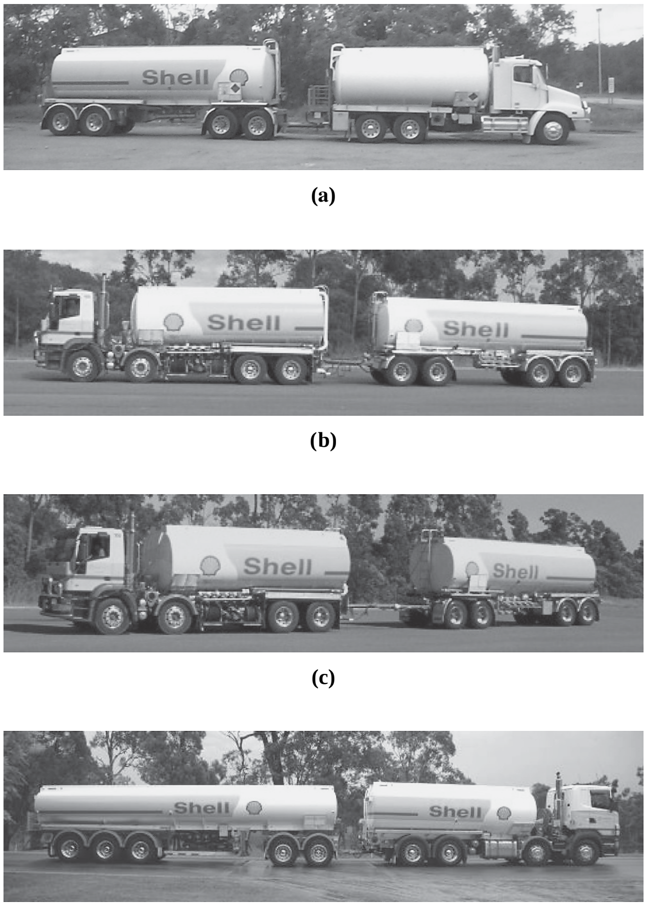
The vehicle design process began with field testing of the company's safest existing vehicles, went on to the iterative design of an improved concept by vehicle dynamics simulation, and ended with field testing and calibrated computer simulation of a prototype vehicle for certification.

The nature of Shell Direct's fuel distribution operations required the following design criteria to be imposed: the configuration needed to be a truck and full trailer (for operational flexibility) and have 22.5 in. wheels (for availability of spare tires in remote areas, underbody clearance in off-road operation, and standardization across the fleet).

These design criteria posed significant challenges for the design team, because truck-trailers are known to be less dynamically stable than the alternative B-double configuration, and low-profile wheels offer a cost-effective improvement in dynamic stability through reduced center-of-gravity height.

Testing the Company's Safest Existing Vehicles

Shell Direct made available two of the better-performing truck-trailer configurations in its fleet for a series of dynamic tests which would ultimately point the way to an improved design concept. Figures 1(*a*) and (*b*) show the two vehicle configurations (variations of which are used widely in Australia by many transport operators). Prescriptive size and weight regulations limit these vehicles to 19 m (62 ft) in length and 50 t (110,000 lb) in mass. With the inherently favorable low-speed off-tracking characteristics of the truck-trailer configuration, there was scope to investigate increased length as a way



(a)

(b)

(c)

(d)

FIGURE 1 Test vehicles: (*a*) three-axle truck and four-axle trailer, from existing fleet; (*b*) four-axle truck and four-axle trailer, from existing fleet; (*c*) four-axle truck and four-axle trailer, with longer drawbar; and (*d*) four-axle truck and five-axle trailer, final design concept.

of improving dynamic stability without compromising road space requirements. Figure 1(*c*) shows how the trailer in Figure 1(*a*) and the truck in Figure 1(*b*) were combined (with a longer drawbar) to arrive at a 22-m (72-ft), 55-t (121,000-lb) speculative configuration. This configuration's safety performance was superior to that of the two existing vehicles. Iterative refinement of this configuration (described in a later section of this paper) went on to produce the final design concept shown in Figure 1(*d*), with the main differences being an additional axle on the trailer and a longer, lower tank. Shell Direct has named the configuration 22-m-long 55-t vehicle SD2255.

The following tests were selectively used to assess the performance of the existing Shell Direct vehicles and to provide a basis on which to drive the design process. The complete set of tests was ultimately applied to the SD2255. Full details of the performance tests are available (*2*).

Lane Change Maneuver

A lane change maneuver is the test method used to measure the rearward amplification (RA) and high-speed transient off-tracking (HSTO) of a vehicle combination. RA generally pertains to heavy vehicles with more than one articulation point, such as truck-trailers and road-train combinations. RA describes the tendency for the trailing unit (or units) to experience higher lateral acceleration than the hauling unit during a dynamic maneuver. It is a serious safety issue in rapid path-change maneuvers as it can lead to rear-trailer rollover.

As the name suggests, each unit in the combination amplifies the lateral acceleration of the unit immediately ahead of it, and thus amplification of lateral acceleration increases toward the rear of the vehicle. Lower values of rearward amplification indicate better performance. Higher values of rearward amplification imply higher probabilities of rear-trailer rollover.

RA improves with fewer articulation points, a shorter distance from the center of gravity of the hauling unit to the hitch point, roll coupling through turntables at articulation points, shorter coupling rear overhang, longer drawbar lengths, longer trailer wheelbase, and tires with higher cornering stiffness.

The intention of the lane change maneuver is to produce a known lateral acceleration at the steer axle, at a given frequency, and to record the lateral acceleration experienced at the rear unit. The ratio of peak lateral acceleration at the rear unit to that at the steer axle is the RA of the vehicle.

In the lane change maneuver, the lateral displacement of the rear end of the last trailer of an articulated vehicle may overshoot the final path of the front axle of the hauling unit. HSTO is a measure of this lateral overshoot. The HSTO is difficult to measure accurately in the field but can be determined with confidence from a calibrated computer model of the vehicle.

Pulse Steer Input

An important consideration in the stability and handling of heavy vehicles is how quickly yaw or sway oscillations settle down, or decay, after a severe maneuver has been performed. Vehicles that take a long time to settle increase the driver's workload and represent a higher safety risk to other road users and to the driver. The yaw damping coefficient (YDC) performance measure quantifies the rate at which yaw oscillations decay after a short duration steer input (pulse input) at the hauling unit.

The intention of the yaw damping response test is to provide a steering input that will excite the rear unit of the combination into a yawing motion. The maneuver requires that the vehicle be traveling straight, with the steering wheel centered. When safe, the steering wheel is turned rapidly to one side and then back to the center and held there for as long as possible. The steering impulse should take around 0.6 s to complete and result in a steer tire movement of at least 3.2°. The YDC of the vehicle combination is determined from the time history of the yaw motion. A higher YDC means better performance.

YDC is affected by test conditions such as grade and test speed. It is recommended that the test be performed on a grade of less than 1% and at the certified vehicle speed.

Pseudorandom Steer Input

For articulated vehicles there exists a frequency at which maximum rearward amplification occurs. This value is typically within the range from 0.3 to 0.5 Hz. The frequency response of the vehicle indicates frequencies at which the vehicle is most sensitive to lateral acceleration inputs and is the vehicle's natural or resonant frequency. For long combination vehicles it is important that the vehicle's natural frequency not occur at the driver's dominant steering frequency as this can result in excessive rear trailer lateral movement during normal driver steering activity and increased driver workload.

The intention of this test is to provide a steering input at a range of frequencies that will excite the rear unit of the combination into a yawing motion. The steering input and the response of the rear unit are recorded and these data are used to determine the frequency response of the vehicle. This test assesses the vehicle's lateral acceleration gain over a range of input frequencies.

While this test does not form part of the package of PBS, it does provide a full representation of the vehicle system gain in the frequency domain. It is also accepted that lateral acceleration gains measured by the single lane change maneuver and the pseudorandom input test will differ as the two methods have a fundamental difference in terms of the amplitude of input, and thus the nonlinear region to which they apply.

Acceleration Capability

The acceleration capability of a vehicle is important in determining its ability to clear intersections and railway crossings. The acceleration capability test requires the vehicle to accelerate, from rest, at its maximum achievable rate over a distance of 100 m on a zero grade. The profile of distance versus time is recorded and compared with the PBS requirements.

The acceleration capability of a vehicle is strongly influenced by the grade. PBS recommends that the acceleration test be performed in both directions along a given 100 m section of road, and that the results be averaged.

Several vehicle parameters may have an important effect on a vehicle's acceleration performance. Examples include gear change time, gear selection, and throttle position in the lower gears. For these reasons, it is best to determine the acceleration capability of a vehicle in a field test rather than through simulation or, alternatively, to use the results of a field test to determine the most appropriate values to use in a simulation of the vehicle.

Static Rollover Threshold

Rollover stability is the most significant safety issue and arguably the most important performance measure for heavy vehicles because it has been strongly linked to rollover crashes.

The measure of rollover stability is static rollover threshold (SRT), which is the level of lateral acceleration that a vehicle can sustain without rolling over during a turn. The SRT is expressed as a fraction of the acceleration due to gravity, g, where 1g is an acceleration of 9.807 m/s^2, corresponding to the force exerted by the earth's gravitational field. High values of SRT imply better resistance to rollover.

To determine the SRT for a vehicle in an on-road test, the vehicle must be driven along a specified circular path at an initial speed that is at least 10 km/h slower than the speed at which the rollover instability will occur. From the initial speed, the driver must increase the speed of the vehicle at a slow, steady rate until the point of rollover.

This test is expensive to conduct correctly in a physical sense, however, computer simulation models can give very accurate results, particularly if calibrated using test data.

Low-Speed Cornering

The low-speed cornering test allows several important performance indicators to be measured: low-speed swept path, frontal swing, tail swing, and steer tire friction demand.

The low-speed cornering maneuver can be executed well in a field test; however, because there are several well-validated simulation packages available for the task, it is typical to use simulation to conduct the low-speed cornering test. It is also much easier to measure steer tire friction demand in simulation than in a field test.

Startability and Gradeability

The startability test determines the maximum grade on which a vehicle can start and maintain forward motion. Gradeability includes two tests, the first, being similar to that for startability, determines the maximum grade on which a vehicle can sustain forward motion, from a moving start. Typically, this is higher than the maximum grade determined in the startability test. The second test for gradeability is to determine the maximum speed attainable on a 1% grade.

Unlike acceleration capability, parameters affecting startability and gradeability are generally well known. Using simulation alone is, therefore, considered valid in the assessment of these measures. It is also relatively challenging to find roads with the required grades to carry out these tests in the field; thus simulation is the typical approach.

Tracking Ability on Straight Path

The tracking ability on a straight path test aims to measure the dynamic lateral movement of the rear end of a vehicle when it is traveling in a straight line along a road with specified roughness and crossfall. The swept width of the vehicle needs to be recorded in this test and compared with the PBS requirements.

Iterative Design of Improved Concept by Vehicle Dynamics Simulation

Testing of Shell Direct's two existing 19-m, 50-t vehicle configurations and the speculative 22-m, 55-t vehicle configuration showed that the 22-m, 55-t vehicle configuration demonstrated the best safety-performance. Vehicle dynamics simulation was then used to improve the design of the speculative configuration iteratively so that it could satisfy the complete set of PBS safety-related standards.

The performance standard that was most influential in the design of the vehicle configuration was HSTO. HSTO is notoriously difficult for conventional truck-trailers to satisfy, so this standard was used to check every design iteration until a satisfactory design was achieved.

The authors' backgrounds in the assessment of truck-trailer configurations include research undertaken for the NTC to determine the sensitivity of truck-trailer performance to changes in vehicle dimensions (*3*). Dimensions affecting truck-trailer dynamics most greatly were found to be truck wheelbase, trailer wheelbase, coupling rear overhang, and trailer center-of-gravity height. A three-axle truck and four-axle trailer was one of the truck-trailer configurations used to quantify the sensitivity of truck-trailer performance to dimensional changes. The following relative sensitivities were found for each dimension:

- Trailer wheelbase: 1.00,
- Truck wheelbase: 1.24,
- Coupling rear overhang: 3.00, and
- Trailer center-of-gravity height: 14.1

This shows that trailer center-of-gravity height is most important, while coupling rear overhang is still considerably important. Truck and trailer wheelbases are similar in sensitivity. Other parameters affecting performance include suspension roll-stiffness and suspension roll-steer coefficient. These parameters work hand-in-hand to affect lateral stability and directional performance.

Truck Optimization

The obvious problem that arises when a truck-trailer configuration is being designed for good dynamic performance is management of the trade-off between increased dimensional requirements. As a general rule of thumb, it is recommended to maximize truck and trailer wheelbase to increase the directional stability of each unit respectively. Maximizing truck and trailer wheelbase also yields the opportunity to extend load-space length and reduce overall height, thereby simultaneously decreasing center-of-gravity height. The extent to which each unit is lengthened is primarily controlled by the truck manufacturer, as truck wheelbases tend to be available in a small number of fixed variants, while trailer manufacturers can generally build trailers to custom length.

Previous work by the authors (*3*) clearly shows that coupling rear overhang is best set to as small a value as possible. This reduces the lateral movement of the coupling brought about by the lever effect of the truck as it rotates in the yaw-plane about the drive axle group during travel; a larger coupling rear overhang will result in more lateral movement of the coupling, in turn providing unwanted input to the trailer. European convention is to place couplings extremely close to the drive axles, even though body rear overhang may be large. Australian convention is to place the coupling 100 to 200 mm (4 to 8 in.) in from the rearmost point on the truck, the primary reason being to aid manual coupling and uncoupling.

Maximizing truck wheelbase and minimizing coupling rear overhang is inherently simple with twin-steer trucks, as the body already needs to be set further forward to give the appropriate load distribution. Long wheelbases are therefore naturally designed into these vehicles, with body rear overhangs not as great as those of single-steer trucks. Therefore, the twin-steer truck lends itself to prudent truck-trailer design.

Trailer Optimization

By far the most critical parameter in truck-trailer stability is the center-of-gravity height of the trailer. This fact alone necessitates a long trailer to reduce overall height. As part of the sensitivity study undertaken for this investigation, the effect of trailer drawbar length was examined by simultaneous reduction of trailer drawbar length and increase of trailer wheelbase by the same amount. This resulted in an equal-length unit with lower center-of-gravity. As long as more of the payload mass was carried by the rear trailer group, performance was improved significantly. This effect was observed even when center-of-gravity height was left unchanged. This phenomenon can be visualized with the aid of Figure 2. For two vehicles traveling around a bend, the amount of off tracking of the rear of each vehicle can be seen at right. The lateral forces generated by the trailer tires result from the sideslip angles of the tires in relation to their direction of travel. Case (a) requires a greater slip angle to be generated to overcome the greater side load which, considering the additional length of the drawbar, requires the front of the trailer to move toward the outside of the bend considerably more than in Case (b), where the reduced slip angle requirement (because of lighter load) and the short drawbar results in less off-tracking of the front of the trailer and hence less off-tracking of the rear of the trailer.

Designing Within a Limited Overall Length

Developing a dynamically stable truck-trailer configuration within a limited overall length limit requires a logical process. The following steps were undertaken to arrive at the SD2255 design concept:

1. Select a twin-steer truck with a medium-to-long wheelbase. The length of the truck should not inhibit the length of the trailer, which is more dependent on increased length to provide the lowest possible center-of-gravity height.
2. Determine the lowest possible tank cross-section for the truck such that the required payload volume can be achieved without unreasonable length (i.e., a large barrel rear overhang should not undermine good load distribution).
3. Set the coupling rear overhang to a minimum.
4. Determine the lowest possible tank cross section for the trailer that allows the required payload to be carried within the desired overall length.
5. Set the drawbar to a minimum practical length.
6. Check load distribution.
7. Check performance against PBS and redesign if necessary.

Part of the design process was to add a third axle to the rear axle group so that all the performance standards could be satisfied. One aspect of the design that was developed using this process could not be achieved at the manufacturing stage. The coupling rear overhang was required to be set back around 300 mm (12 in.) further than the concept design, with a corresponding amount taken out of the trailer wheelbase. Figure 3 shows the final layout of the vehicle.

FIELD TESTING AND CALIBRATED SIMULATION OF THE DESIGN CONCEPT

Assessment of a potential PBS vehicle can be conducted by either field testing, computer simulation, or a hybrid approach. The most credible assessments are achieved using a hybrid approach that uses information collected from field tests under real-world conditions to calibrate a computer model, which is then used to simulate the vehicle under ideal conditions. Real-world conditions, which often interfere with the quality of test results, include road crossfall, driver steering accuracy, vehicle loading, and test speed. Once the models are calibrated

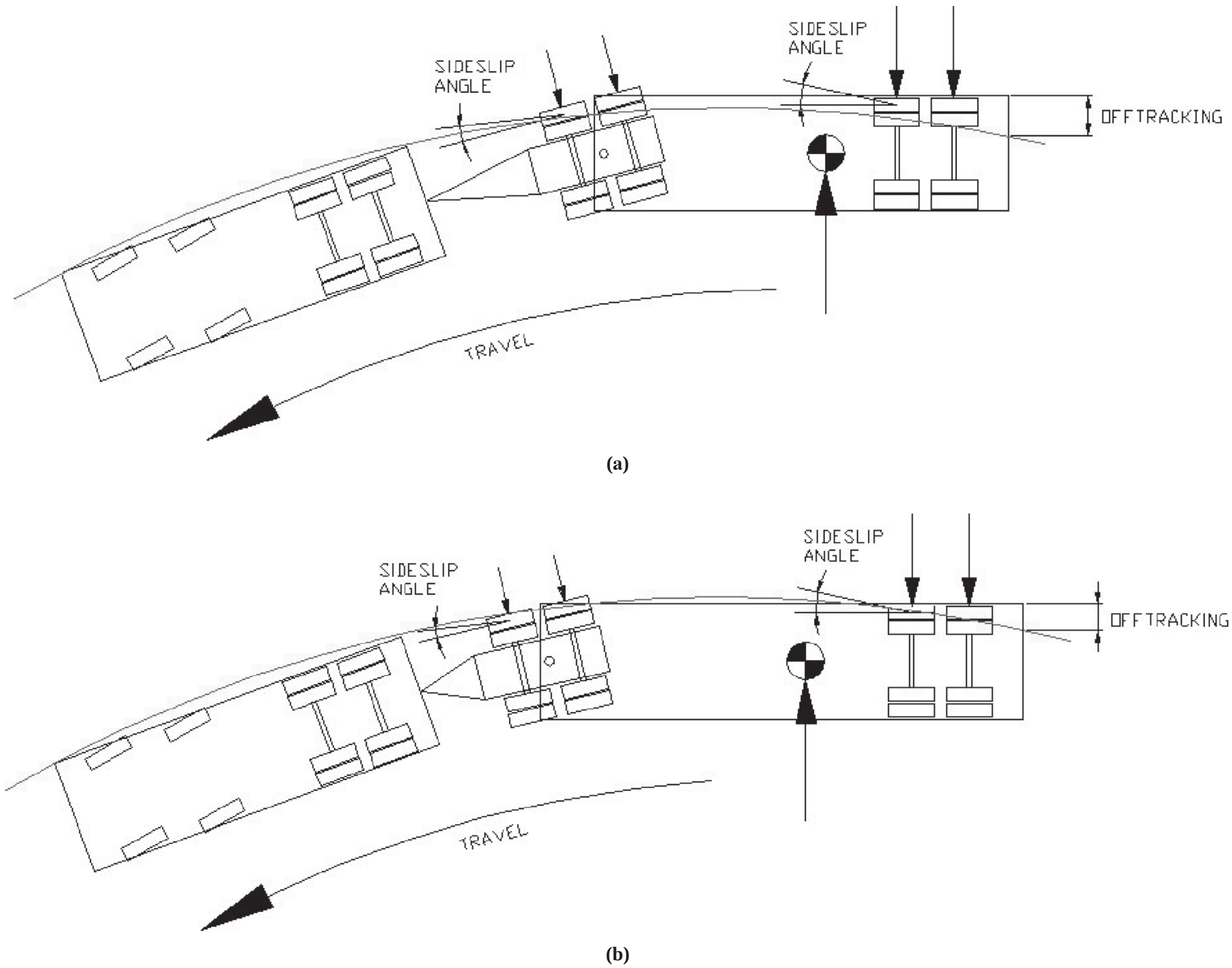


FIGURE 2 Effect of trailer drawbar length on vehicle dynamic performance: (*a*) long drawbar, short trailer, and (*b*) short drawbar, long trailer.

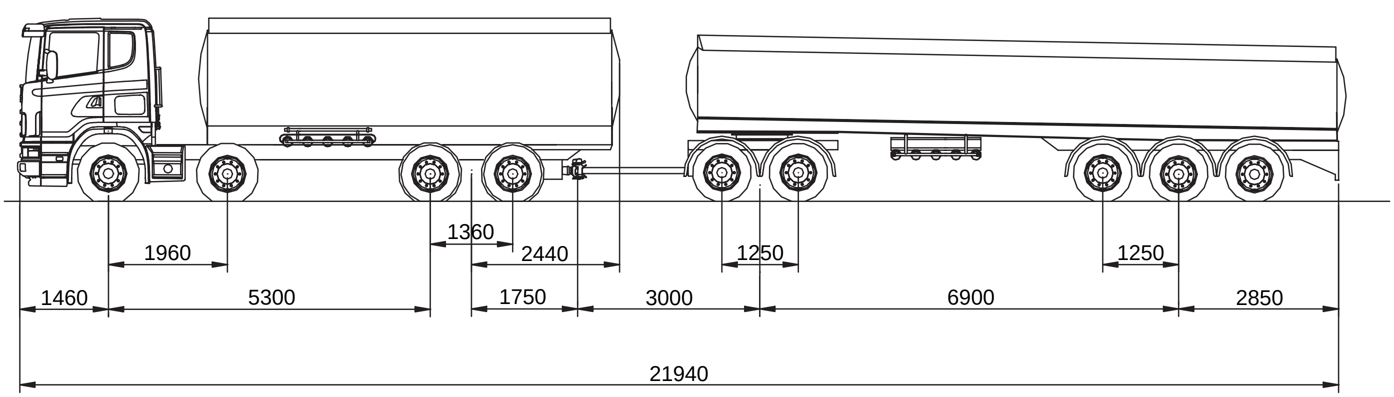


FIGURE 3 Layout of design concept (units in millimeters).

(a) (b)

FIGURE 4 SD2255 truck trailer undergoing dynamic lane change testing: (*a*) vehicle executing test maneuver and (*b*) test course layouts.

under the real-world test conditions, they can be used to evaluate the performance of the vehicles under standard conditions (i.e., flat road surface with correct driver steer input, axle loads, and test speeds).

Field tests performed by ARRB Group on the SD2255 included pseudorandom steer inputs, acceleration capability, and lane change maneuvers. A tilt test was independently performed on the truck by Queensland Transport. All these tests were used to calibrate the simulation model of the SD2255 for subsequent assessment against PBS.

Figure 4 shows the SD2255 undergoing a dynamic lane change maneuver. Lane changes were conducted at a speed of 88 km/h (55 mph) at frequencies of 0.3, 0.4, and 0.5 Hz. The highest RA was observed at 0.4 Hz, which was in agreement with the results of the pseudorandom steering input tests (slightly above 0.4 Hz). The frequency response measured in the pseudorandom steering input tests is shown in Figure 5 compared with the results obtained from the simulation. While the simulation returned a slightly greater peak gain, the form of the plot and the frequency of the peak gain were in close agreement with the experimental results.

The acceleration capability tests showed that the simulation model could be calibrated to perform almost exactly as the measured response. Figure 6 shows simulated and experimental results for acceleration tests in the uphill and downhill directions, as well as a simulated flat road test.

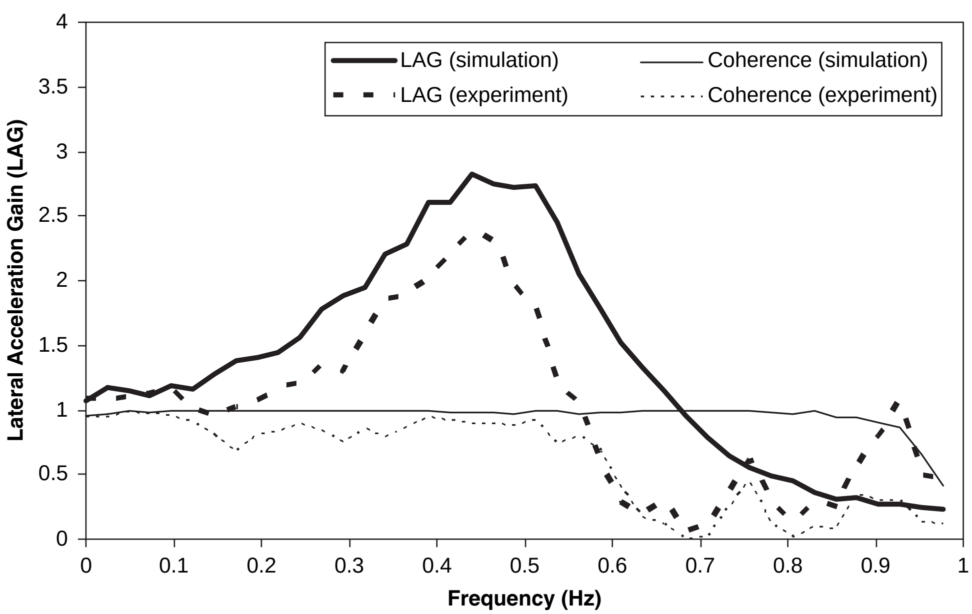


FIGURE 5 Pseudorandom steer input frequency response (simulation versus experiment).

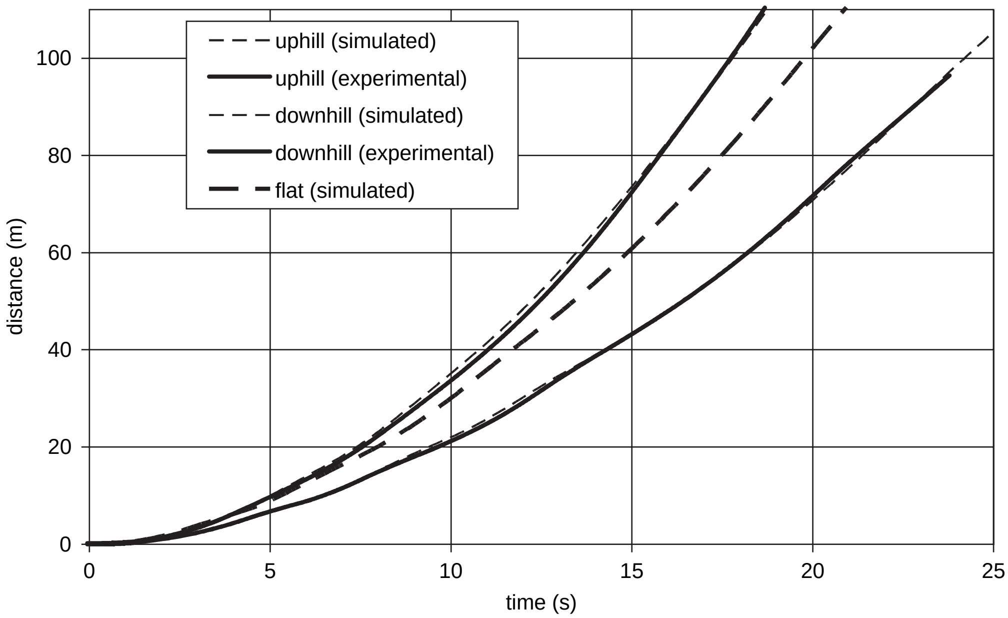


FIGURE 6 Acceleration capability (simulation versus experiment).

The dynamic lane changes provided performance data on RA and HSTO, which could be compared between simulation and experiment. In the field tests, RA and HSTO were 2.24 and 0.51 m (1.67 ft), respectively, while in the simulation (performed for the as-tested vehicle on the real-world geometry of the test site) the results were 2.02 and 0.44 m (1.44 ft), respectively.

Static rollover threshold could not be compared directly with the field test, because the field test was only conducted to the point of first axle lift. However, the point of first axle lift (0.44*g*) matched exactly with the point of first axle lift determined from the simulation.

The calibrated simulation model was used to obtain performance characteristics for all the tested standards under ideal conditions and for tests that were not performed in the test program (e.g., tracking ability on a straight path). Figure 7 shows a comparison of the lane change performance observed during the field test with that demonstrated by the simulation model. Figure 8 shows the subsequent calibrated simulation of the tracking ability on a straight path test.

CONCLUSION

The integrity of the PBS system is heavily reliant on the consistency and quality of the assessments. The assessment process detailed in this paper has proven to be a reliable and robust method of certifying potential PBS vehicles. With the hybrid method of assessment, the

(a)

(b)

FIGURE 7 Comparison of (*a*) test and (*b*) simulation with AutoSim (lane-change maneuver).

FIGURE 8 **Simulation of trucking ability on a straight path with AutoSim.**

drawbacks of field testing (e.g., nonideal conditions) are offset by the ideal nature of computer simulation. Likewise, computer simulation alone probably cannot be deemed to be of certification quality without some form of field testing. The combination of these two assessment methods ensures a robust assessment is made.

The Shell Direct project is a sound case study for Australia to learn from in the early stages of the PBS regulatory regime. The project has resulted in the development of a truck-trailer configuration that exceeds prescriptive size and weight limits but demonstrates safety-performance that is suitable for unrestricted access to the road network in the eyes of PBS.

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