Proposed updates of PBS Standards: Static Rollover Threshold, Rearward Amplification and High-Speed Transient Offtracking

Technical Discussion Paper

November 2025

Executive Summary

In 2018 Transport and Infrastructure Ministers endorsed the recommendations of the National Transport Commission (NTC) policy paper '*Reforming the PBS Scheme*'. This document represents the latest step in implementing those recommendations. Specifically, this paper covers the review of three PBS standards: Static Rollover Threshold (SRT), Rearward Amplification (RA), and High-Speed Transient Offtracking (HSTO).

To inform the content and direction of the review, the NHVR developed a range of options and presented those to the PBS Review Panel. The PRP review identified the following key principles:

- PBS requirements represent best-practice safety standards and should continue to be upheld
- Wherever possible, PBS should support the shift from prescriptive vehicle designs to PBS vehicles that deliver higher levels of safety than typical industry performance
- Proven and reliable vehicle technologies can further enhance safety in real-world operation.

Within this context, the Panel provided direction on which of those options should be advanced for further technical analysis and industry review and consultation. This document provides the engineering assessment of the preferred options.

While the existing PBS Vehicle Standards and Assessment Rules do not specifically limit the application of technologies in order to meet PBS requirements, some of the existing assessment methods in the rules do not readily allow the use of advance technology in PBS designs. For example, the constant speed lane change manoeuvre test does not accommodate the use of electronic stability controls to prevent roll-over.

In this context, the NHVR makes the following recommendations:

- For SRT, the introduction of an additional and optional, technology-dependent performance assessment pathway within the range 0.32g ≤ SRT < 0.35g for combinations fitted with ESC/RSC on all units is proposed. Access to this pathway would be conditional on demonstrating equivalent or better dynamic performance to existing PBS requirements through specified manoeuvres and additionally meeting the dynamic measure of Load Transfer Ratio (LTR ≤ 0.9). This recognises the demonstrated capacity of stability control to mitigate rollover risk, while preventing vehicles from operating at or near full wheel lift. The existing 0.35g and 0.40g limits would remain available as a non-technology pathway.
- For SRT requirements for dangerous goods vehicles, it is proposed that:
  - The definition of a *road tank* vehicle be amended to resolve ambiguity and close a long-standing gap within the Rules.
  - A new requirement be set of an SRT of not less than 0.37g for vehicles carrying dangerous goods in bulk within a portable or demountable tank with a capacity of more than 7,500 litres. This recognises the practical physical and loading constraints, while still ensuring a higher safety profile for the fleet.
- For RA and HSTO, the paper proposes two complementary additions to the existing standards.
  - Firstly, an alternative optional pathway is proposed to allow for ESC/RSC to be included in the standard lane-change assessment for vehicles with an SRT not less than 0.32g (but coupled with an additional LTR ≤ 0.9 criterion). This would include appropriate speed requirements in place of the current constant-speed rule, such that vehicles can be assessed in a way that accommodates the automatic braking response of RSC/ESC.
  - Secondly, the introduction of a reference-vehicle approach for combinations that cannot physically attain 88 km/h. This would require the subject vehicle's RA, HSTO and LTR at its maximum achievable speed being no worse than those of a suitable PBS-approved reference vehicle at the same speed.
- Finally, the introduction of LTR to be utilised as a supplementary control to capture dynamic behaviour and susceptibility to instability in circumstances where RA, HSTO and SRT alone may not fully establish vehicle behaviour. An LTR limit of 0.9 is applied wherever alternative test speeds or technology-based SRT pathways are used.

Taken together, the recommended changes do not relax the safety expectations of the PBS Scheme. Rather, these proposals reflect "the effects of new technology and catering to future technology" as envisaged in the 2018 recommendations of the Ministers.

The proposals provide clarity, broaden the treatment of test speed in assessment manoeuvres, and further develop the Rules to incorporate modern technological advancements. These proposals introduce an alternative SRT pathway whereby combinations in the range 0.32g ≤ SRT < 0.35g may be approved where they are fitted with stability control and, critically, demonstrate satisfactory dynamic performance. The inclusion of LTR ≤ 0.9 on specific manoeuvres for these vehicles provides a direct constraint on threshold behaviour, addressing an existing limitation in the current framework.

The proposal for changes to the RA and HSTO Standards provides a pathway for vehicles that do not meet the test-speed required under the current assessment method and recognises the role of ESC/RSC, with the addition of a LTR test, in achieving PBS outcomes.

Essentially, the proposals operate in two distinct ways. The clarification of dangerous goods SRT refines the baseline requirements, while the alternative-speed and technology-based assessment pathways provide a further, optional assessment method and entry to the Scheme.

Collectively, these recommendations enable and encourage further improvements in the safety and productivity of Australia's heavy vehicle fleet through innovative approaches to vehicle performance, in keeping with the fundamental aims of the PBS Scheme.

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1 Introduction

Consultation

Consultation period: **21 November 2025 – 23 January 2026.**

Use the Feedback Form provided. All feedback should be submitted via email to pbsreview@nhvr.gov.au.

When submitting feedback, please include 'PBS High-Speed and Stability Standards Review Feedback – [Your Organisation]' in the email subject line.

In 2018 Transport and Infrastructure Ministers endorsed the recommendations of the National Transport Commission (NTC) policy paper '*Reforming the PBS Scheme*'.

This document is the latest step in implementing those recommendations. Specifically, this paper presents the review of three PBS standards: Static Rollover Threshold (SRT), Rearward Amplification (RA), and High-Speed Transient Offtracking (HSTO).

To inform the content and direction of the review, the NHVR developed a range of options and presented those to the PBS Review Panel. The Panel provided direction on which of those options should be advanced for further technical analysis and industry consultation. This document provides the engineering assessment of the preferred options.

The NHVR is committed to collaborating closely with industry and regulatory stakeholders to ensure that any changes to the PBS standards are practical and effective. To this end, feedback is welcomed on the proposed approaches to support further refinement and implementation planning.

1.1 Options considered by PRP

The following is a brief summary of each option presented to the PRP. Discussions were held between the NHVR and PRP members and feedback was received on the options, including confirmation of those that were supported in principle.

1.1.1 Static Rollover Threshold (SRT)

Option 1 – Continue with Current Standard

No changes are made to the standard. Progression of this option suggests that the current test specification and performance levels are still fit for purpose and are not limiting innovation in vehicle design.

Option 2 – Revised performance level if vehicle is fitted with rollover control technology and complies with supplementary test procedure (selected for progression – see Section 2.1 for further details)

Since the development of the current SRT standard in the early 2000s, the adoption of stability control technology in heavy vehicles has grown substantially. This option proposed updating the SRT standard to recognise the safety benefits these technologies provide in reducing rollover risk. The update would introduce an alternative performance level for vehicles equipped with such technology, provided they demonstrate equivalent performance to the current standard through a supplementary testing procedure. As most PBS vehicle combinations are assessed using numerical modelling methods, it is essential to explore how the functionality of this technology can be incorporated into the assessment. Additionally, factors such as the reliability of these systems must be carefully considered.

Option 3 – Reduced SRT Limit for Livestock Vehicles to Increase Participation

Despite the popularity of the PBS Scheme, certain vehicle types are under-represented, with uptake of Livestock-carrier vehicles particularly low. These vehicle combinations have a high centre of gravity when loaded, making it difficult to comply with the SRT standard. Since the origins of the PBS standards are based on the performance of the prescriptive fleet, this option proposed that the granularity of the SRT performance values be increased to provide a new, reduced limit for Livestock-carrier vehicles. This new limit would be toward the upper end of the prescriptive fleet performance so that overall fleet performance would be improved by increased PBS participation. The NHVR considered this option, however incorporation of these vehicles into Option 2 renders that option redundant, whereby Option 2 would not be limited to specific freight tasks but rather address vehicle performance, thus better embodying the intent of the Scheme.

Option 4 – Investigation into the Application of the 0.4g Performance Level for Dangerous Goods Vehicles (selected for progression – see Section 2.2 for further details)

The NHVR has received industry feedback that there is ambiguity regarding which Dangerous Goods (DG) vehicles are required comply with the higher 0.4g performance level, specifically ISO tanks and portable tanks. This option proposed that an investigation be conducted into which DG vehicles should be required to comply with the 0.4g performance criteria. This investigation will include whether the current wording of the requirement is fit for purpose or whether any additional clarification is necessary.

Rearward Amplification (RA)

Option 1 – Continue with Current Standard

No changes are made to the standard. Progression of this option suggests that the current test specification and performance levels are still fit for purpose and are not limiting innovation in vehicle design.

Option 2 – Update the Standard to Accommodate Stability Control Technology (selected for progression – see Section 3.1 for further details)

The intent of the Rearward Amplification standard is to limit the risk of rear-trailer rollover. Since stability control technology can help manage this risk, this option proposed updates to accommodate the use of this technology during the RA test procedure. Like SRT Option 2 above, it is essential to explore how the functionality of this technology can be incorporated in the simulation environment. Additionally, factors such as the reliability of these systems must also be carefully considered.

Option 3a – Reduce Vehicle Test Speed for Level 4 Vehicles

Similar to Livestock-carrier vehicles discussed above, Level 4 vehicles have low uptake within the PBS Scheme, making up less than 1% of the PBS fleet. This can be partially attributed to the difficulty encountered for these vehicles complying with the RA standard. This option proposed that the vehicle speed for the RA test procedure be reduced from 88 km/h to 78 km/h, similar to a recommendation to the *Austroads PBS Level 3 and 4 Standards Review* (Coleman et al. 2015). Unlike (Coleman et al. 2015), a steer frequency of 0.4Hz and maximum lateral acceleration not less than 0.15g would be retained for the test procedure which retains compliance with the base standard ISO 14791:2000(E). Since the existing Type II road train fleet would still have difficulty passing this standard at the reduced test speed, this proposal aligns with the Scheme's intent to lift productivity while maintaining or improving fleet safety performance.

Option 3b – Reduce Vehicle Test Speed for Vehicles Unable to Achieve 88 km/h (selected for progression – see Section 3.2 for further details)

The test procedure specified for the RA standard requires vehicles to be assessed at 88 km/h. Vehicles that are unable to achieve this speed are deemed to fail the standard. While rare, vehicles which cannot reach 88 km/h have attempted to access the PBS Scheme in the past. This option proposed an alternative approach to satisfying the RA standard via comparison with an approved PBS vehicle at a different test speed. As the relationship between RA and test speed is non-linear and configuration dependent, it is difficult to set specific performance criteria at speeds other than 88km/h. Instead, a like-for-like comparison demonstrates that the subject vehicle does not pose any additional risk than an otherwise approved PBS vehicle.

This proposal represents an alternative pathway which constitutes the translation of the existing PBS requirements for a lower speed environment. This is in effect, the implementation in more concrete terms of a specific application of the already established PBS exemption process under Section 9 whereby, “The Regulator may consider that while a heavy vehicle built to a design does not comply with a standard under the Standards and Vehicle Assessment Rules, it will not pose any greater risk than a heavy vehicle that complies with the standard”.

Option 4 – Introduce an Additional Measure: Load Transfer Ratio (selected for progression but as a supplementary measure used in other options)

Anecdotal evidence as well as internal analysis performed by the NHVR suggest that the RA test procedure is not as robust as intended for certain vehicle combination types. In certain rare cases, some combinations can pass the RA standard even if the wheels on the rear trailer unit lose contact with the ground. Although these cases are rare, it suggests that additional measures could be beneficial to prevent these occurrences. In the context of the PBS Scheme, Load Transfer Ratio (LTR) is defined as “the proportion of vertical load imposed on the tyres on one side of a vehicle unit that is transferred to the other side of the vehicle unit during a standard lane change manoeuvre” (Prem et al. 2001b, 2001c). RA Option 4 proposed that LTR be introduced as an additional requirement to account for the limitations in the Rearward Amplification standard.

High-Speed Transient Offtracking (HSTO)

Option 1 – Continue with Current Standard

No changes are made to the standard. Progression of this option suggests that the current test specification and performance levels are still fit for purpose and are not limiting innovation in vehicle design.

Option 2 – Update the Standard to Accommodate Stability Control Technology (selected for progression – see Section 3.1 for further details)

The intent of the HSTO standard is to manage safety risk by limiting the sway of the rearmost trailers of multi-articulated PBS vehicles in avoidance manoeuvres performed without braking. This manoeuvre is the same as that of that used in the assessment of the RA. Since stability control technology may improve the management of this risk, this option proposed updates to accommodate the use of this technology during the HSTO test procedure. Like SRT Option 2 above, it is essential to explore how the functionality of this technology can be incorporated in the simulation environment. Additionally, factors such as the reliability of these systems must also be carefully considered.

Option 3 – Reduce Vehicle Test Speed for Vehicles Unable to Achieve 88 km/h (selected for progression – see Section 3.2 for further details)

As with RA Option 3b above, the test procedure specified for the HSTO standard requires vehicles to be assessed at 88 km/h. Vehicles that are unable to achieve this speed are deemed to fail the standard. This option proposed an alternative approach to satisfying the HSTO standard via comparison with an approved PBS vehicle at an alternative test speed. This like-for-like comparison demonstrates that the subject vehicle does not pose any additional risk than an otherwise approved PBS vehicle.

This proposal represents an alternative pathway which constitutes the translation of the existing PBS requirements for a lower speed environment. This is in effect, the implementation in more concrete terms of a specific application of the already established PBS exemption process under Section 9 whereby, “The Regulator may consider that while a heavy vehicle built to a design does not comply with a standard under the Standards and Vehicle Assessment Rules, it will not pose any greater risk than a heavy vehicle that complies with the standard”.

Option 4 – Revise Performance Levels Based on Prescriptive Fleet

Like RA, the HSTO standard is acting as a barrier for entry for certain combination types, particularly Level 3 and Level 4 vehicles. Consequently, these vehicles make up only 15% of the PBS fleet. The *Austroads PBS Level 3 and 4 Standards Review* determined that HSTO is the limiting standard for Level 3 and 4 vehicles and that adjustment is necessary to allow greater participation of these vehicles in the Scheme (Coleman et al. 2015). Option 4 proposed that the test procedure for this standard be reduced from 88 km/h to 78 km/h for Level 4 vehicles to align with RA Option 3a. It is also proposed that the performance levels for the HSTO standard be increased to 1.4m and 1.8m for Level 3 and Level 4 vehicles, respectively. This aligns with recommendations in the *Austroads PBS Level 3 and 4 Standards Review.*

Option 5 – Modify the Method for Calculating Offtracking

The HSTO measure can be viewed as an indication of the severity of intrusion into an adjacent or opposing lane, striking a kerb, dropping off the road seal or colliding with roadside objects (NHVR 2022). The current method for measuring offtracking does not consider vehicle geometry which limits the standard's ability to control the road space taken up during the test manoeuvre. This option proposed a more direct measurement of offtracking in the context of the standard's intent by accounting for vehicle width.

1.2 Recommended Options

Following on from discussions between the NHVR and the PRP, it was decided to further develop approaches that incorporated the following:

For SRT:

- Part I: Revised performance level if vehicle is fitted with rollover control technology and complies with supplementary test procedure (with LTR used as an additional measure)
- Part II: Address the ambiguity in the application of the performance level for DG vehicles

For RA and HSTO:

- Part I: Update the standard to accommodate stability control technology (with the incorporation of LTR)
- Part II: Reduce vehicle test speed for vehicles unable to achieve 88km/h (with the incorporation of LTR)

These options received significant in-principle support from the PRP but required further technical analysis to ensure they are fit for purpose.

1.3 Background

1.3.1 Performance Based Standards

The development of the national PBS Scheme was an iterative process spanning several years. Initially proposed by the National Road Transport Commission (NRTC) in 1993 (Sweatman 1993), formal work began in 1999 with funding provided by both the NRTC and Austroads. The project progressed through multiple phases, which included a series of reports commissioned from ARRB Transport Research Group (ARRB) by the NRTC and Austroads (NRTC 1999; NRTC 2000; Prem et al. 2001a-d). These foundational reports identified approximately 100 potential performance measures and corresponding manoeuvres sourced from existing literature. Among the outcomes was a documented methodology to support the proposed performance measures, including the decision to adopt the SAE J2179 lane change manoeuvre (SAE International 1993), originally designed for speeds of 55 miles per hour, and was altered to 88 kilometres per hour for Australian application.

In 2001, the list of performance measures was refined further. The NRTC 2001a report reduced the initial scope from approximately 100 measures to 25, prompting additional analysis and discussions. These underwent more detailed research in NRTC 2001c, which provided justifications and technical support to associated values. Building on this groundwork, the NRTC fleet study (Prem et al. 2002) assessed a sample of 139 representative vehicles from the Australian heavy vehicle fleet against the proposed performance standards. This study was crucial to the evaluation of the alignment of the proposed standards with existing fleet characteristics and the informing and refinement of the PBS framework.

Finally, 16 of the above were adopted into what is now the current Performance Based Standards. It is important to note this summary does not represent a comprehensive account of all reports and developments contributing to the scheme but aims to highlight influential milestones within the process.

1.3.2 Static Rollover Threshold

The primary purpose of this standard is to manage safety risk by limiting the rollover tendency of a PBS vehicle during steady turns. A PBS vehicle must have an SRT of no less than 0.35g. Though where the vehicle is a road tanker hauling DG in bulk, or is a bus or coach, the rollover stability threshold must not be less than 0.4g. SRT is measured in a quasi-*steady-state* or *static* scenario. Since vehicle rollover can occur in transient manoeuvres where dynamic interactions have influence, SRT is only indicative of overall rollover tendency.

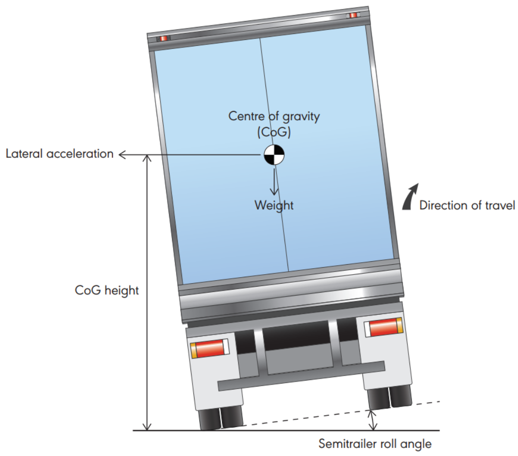

Figure 1 Static Rollover Threshold illustration

Notably, as part of the early research done on performance measures in the NRTC (1999) paper that identified approximately 100 potential performance measures, various researchers suggested that a minimum SRT of 0.32g was appropriate for Australian vehicles. In a subsequent report (NRTC 2000), international performance standards and research were assessed. Findings from multiple sources highlighted that 0.35g was a commonly cited threshold in various international crash studies. Importantly, no specific Australian crash studies have been conducted which support these findings for the Australian context or fleet, which stands unique. A significant international example is a TERNZ crash study (1999), which revealed that 15% of vehicles within the New Zealand fleet exhibited SRT values below 0.35g. This subset of vehicles accounted for 40% of crashes associated with instability or rollover. These findings played a significant role in shaping performance requirements under the PBS framework, particularly for vehicles with an SRT less than 0.35g, which were over-represented in instability-related crashes. Regardless, NRTC (Prem et al. 2001c) detailed the proposed limits for SRT as 0.4g for road tankers and buses, and 0.35g for all other vehicles, which are the minimum SRT values still in use today.

1.3.3 Rearward Amplification

RA is the degree to which the lateral acceleration of the rear unit is amplified compared to the steer axle of the hauling unit in a combination during an avoidance manoeuvre. RA relates to heavy vehicles with more than one articulation point, such as truck-trailers, B-doubles and road train combinations such as A-doubles, A-triples, AB-triples, and B-triples. Such vehicles exhibit a tendency for the trailing unit/s to experience amplified levels of lateral acceleration. Thus, the amount of lateral acceleration exhibited by the trailing units is a safety concern in rapid path change manoeuvres and may lead to loss of control or rollover. The existing PBS RA limit is determined based on the SRT of the rearmost roll-coupled unit in the combination.

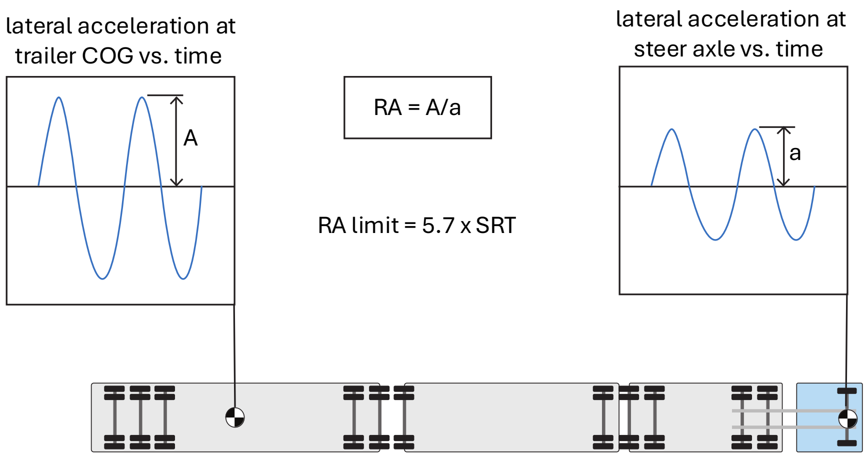

Figure 2 Rearward Amplification illustration

Historically, the performance level for RA was determined to be no greater than 2 (Prem et al. 2001d), when negotiating the SAE J2179 lane change manoeuvre that was adopted for the measure. This maximum was based on tests and analyses of the twin, 28-foot (Western) double in the USA, which at the time was permitted on the entire interstate highway system and measured to have an RA of 2 (Winkler et al. 1992). Hence it was deemed an appropriate baseline anchored in the risk of an existing vehicle operation. The NRTC fleet study (Prem et al. 2002) later refined the RA limit to a vehicle-specific multiple of 5.7 times the SRT. For an SRT of 0.35g this results in an RA of 1.995. The linkage to a vehicle's stability performance enabled vehicles with better stability (i.e. larger SRT values) to take advantage of the resultant increase in RA limit and was determined to be a suitable approach in the fleet study.

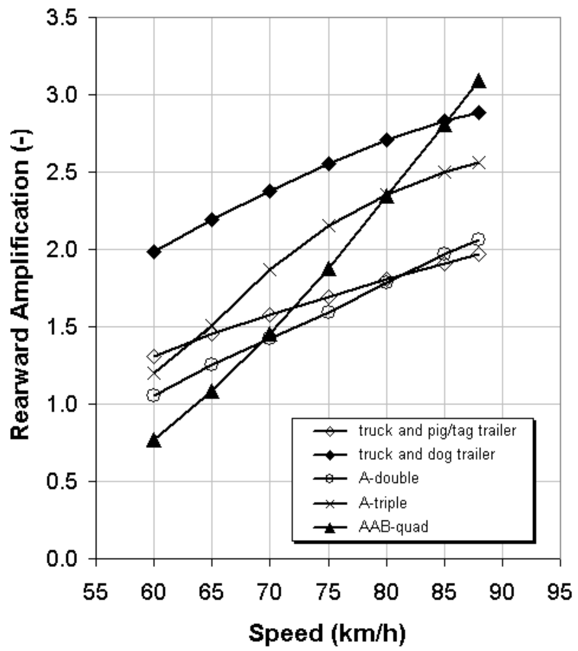

Figure 3 Influence of speed on Rearward Amplification (Prem et al. 2002)

The fleet study observed a non-linearity in the relationship between RA and speed, as shown in Figure 3, further varying between different vehicles. This is an important finding with respect to ensuring a suitable comparison vehicle is used when conducting RA testing for vehicles unable to achieve the 88km/h required speed of the existing RA assessment.

1.3.4 High Speed Transient Offtracking

The purpose of the HSTO standard is to manage the safety risk by limiting the sway of the rearmost trailer in avoidance manoeuvres without braking, at highway speeds. Measured as the distance by which the last axle-group on the rearmost trailer tracks outside the path of the steer axle in a sudden evasive manoeuvre. This may extend beyond or 'overshoot' that of the hauling unit (Figure 4). The amount of HSTO overshoot can be viewed as an indication of the severity of intrusion into an adjacent or opposing lane, striking a kerb or dropping off the road seal (thus increasing risk of a rollover), or collision with a roadside object.

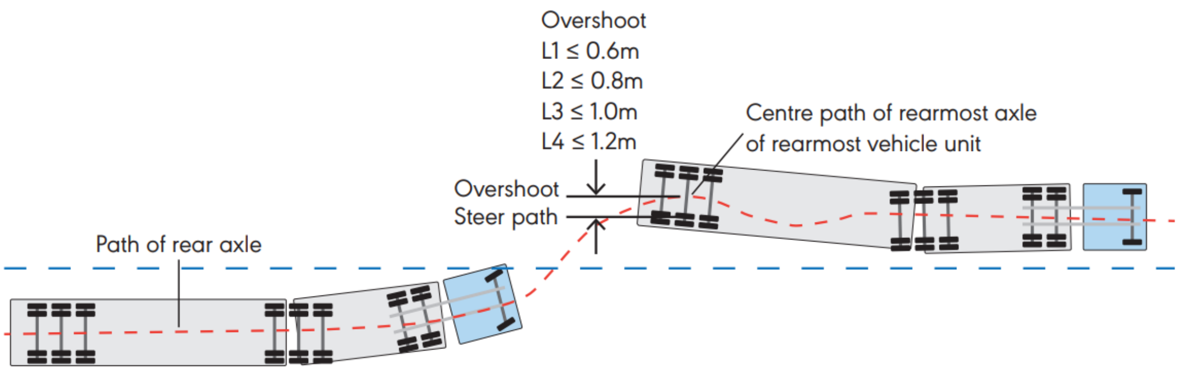

Figure 4 High-Speed Transient Offtracking illustration

The originally proposed HSTO limit (Prem et al. 2001c) was no greater than 0.8m, this was based on international precedent and preliminary findings from research. A significantly larger HSTO value of 1.46m was also considered and based on the SAE J2179 lane change manoeuvre's lateral movement requirement. The fleet study (Prem et al. 2002) revealed that of the 139 vehicles selected to represent the Australian fleet, 96% met a performance level of 1.0m, 94% met 0.8m and 81% met 0.6m. Ultimately it was decided to allocate different HSTO values to certain PBS levels. Where the performance requirement was for a HSTO result no greater than a maximum of 0.6m, 0.8m, 1.0m and 1.2m for PBS levels 1, 2, 3 and 4, respectively.

1.3.5 Load Transfer Ratio (LTR)

Load Transfer Ratio (LTR) is defined as "the proportion of vertical load imposed on the tyres on one side of a vehicle unit that is transferred to the other side of the vehicle unit during a standard lane change manoeuvre" (Prem et al. 2001b, 2001c). In practice, LTR is a measure of how much weight shifts between the tyres on opposite sides of a vehicle when it is turning or performing sudden manoeuvres as compared to the total load.

An LTR of 0.0 means the vehicle's total vertical load is perfectly balanced between the tyres on the left and right sides, with no weight shifting during the turn. An LTR of 1.0, on the other hand, means all the load has transferred to one side, potentially causing the unloaded tyres on the opposite side to lift off the ground completely, leading to vehicle instability.

Importantly, as a dynamic value, LTR shows how close a vehicle is to tipping over during manoeuvres, with higher values indicating the vehicle is nearer to a risk of rollover. A visual description of the LTR at 0 and 1 is shown in Figure 5.

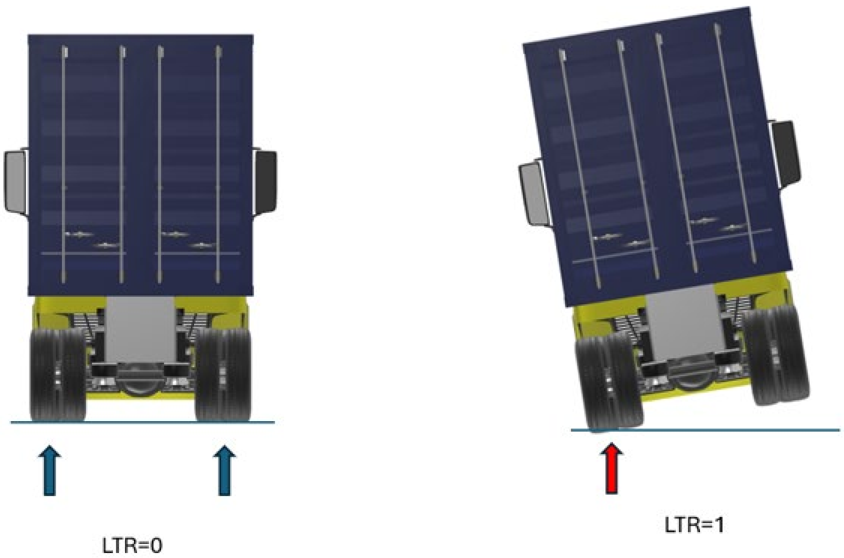

Figure 5 Visual depiction of a vehicle at LTR=0 and LTR=1

LTR was included for consideration in the initial development of the Australian NHVR PBS Scheme as one of the 25 measures “developed to a useable standard” (NRTC 2001c) which ultimately did not become one of the final 16 measures. Initially, the proposed LTR standard was considered with a maximum value of 0.6, however, in environments where the speed is less than 75km/h, the constraint was suggested to be relaxed to 0.75.

In addition to being difficult to assess through field testing, this standard was asserted as redundant on account of its high correlation to the SRT and RA measures (Prem et al. 2002). This outlook resulted in the exclusion of LTR as a standard in Australia’s PBS Scheme. However, this argument was drawn using rudimentary modelling approaches which have been far outpaced by modern numerical approaches. That is, contemporary PBS assessments are overwhelmingly conducted using numerical modelling which renders the difficulties in obtaining the LTR through field-testing as irrelevant. Furthermore, while possibly overlooked on account of the computational methods of the time, a deficiency exists within the current standards which could be addressed by incorporating the consideration of LTR. That is, it is possible for a vehicle to achieve PBS compliance while still exhibiting a poor LTR, revealing an unstable dynamic behaviour that the existing standards are not equipped to fully assess.

Shown in Figure 6 is a compliant PBS vehicle that passes the HSTO performance limit for Level 2, however the vehicle’s LTR during the manoeuvre dwells about 1.0, underscoring where the dynamic performance of a vehicle in the lane change manoeuvre is better captured by the LTR but not HSTO.

Figure 6 A compliant L2 PBS Truck and Dog passing HSTO with an LTR of 1 (w. right side wheels in the air)

Supporting the above advocacy for change, the FALCON ("Freight and Logistics in a Multimodal Context") project was a recent initiative aimed at developing a proposed European PBS framework, taking significant inspiration from existing schemes, particularly the Australian PBS framework (de Saxe et al. 2019). The inclusion of LTR was explored in the project, along with the rationale behind its exclusion from the Australian PBS.

The project ultimately recommended including both LTR and RA measures, determining that the difficulty of experimentally testing LTR was no longer a concern due to the prevalence of computer simulations for vehicle assessments. LTR is considered a more direct measure of rollover risk while juxtaposing RA as still beneficial for assessing the "whiplash" phenomenon. In the absence of an established Australian LTR standard, the FALCON project drew on the Canadian PBS scheme, which incorporates LTR (ACEA 2012).

1.3.6 Occurrences of Rollover Events

The NHVR has reviewed the latest recorded crash data from publicly available records, which shows, as in Figure 7, that truck or heavy vehicle rollover crashes are most prevalent in high-speed zones, with comparatively fewer events in low-speed zones. Notably, there is an increase in rollovers in 60-70km/h speed zones, potentially due to the higher frequency of these zones compared to 80-90km/h zones, or other contributing factors such as speeding or driver error. Overwhelmingly, from the available data, the indication is that the majority of rollover incidents recorded and attributed to heavy vehicles occur at high speeds.

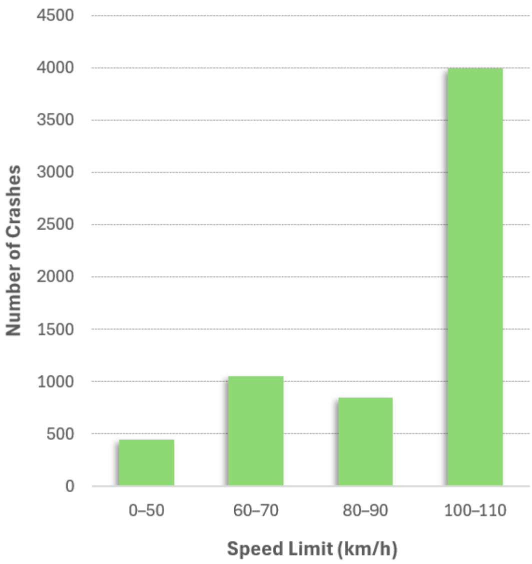

Figure 7 Number of rollover crashes due to heavy vehicle rollover based on recent historical QLD and NSW data

The perception that a higher frequency of heavy vehicle rollovers occur within low-speed zones is diametrically opposed to the latest data. Where this disparity can be further demonstrated using count-based heat maps for Queensland in Figure 8 and for Victoria in Figure 9. In the lowest speed zones (0-50km/h) demonstrated in the graphs on the left (graph (a)), there are notably fewer 'truck' recorded rollover events compared to the highest speed zones (100-110/km/h) demonstrated in the graphs on the right (graph (b)), where there is a substantial occurrence of crashes. Whether these incorporate light trucks along with heavy vehicles is uncertain in the Queensland data; while Victorian data explicitly attributes the rollover with the category of "heavy vehicle".

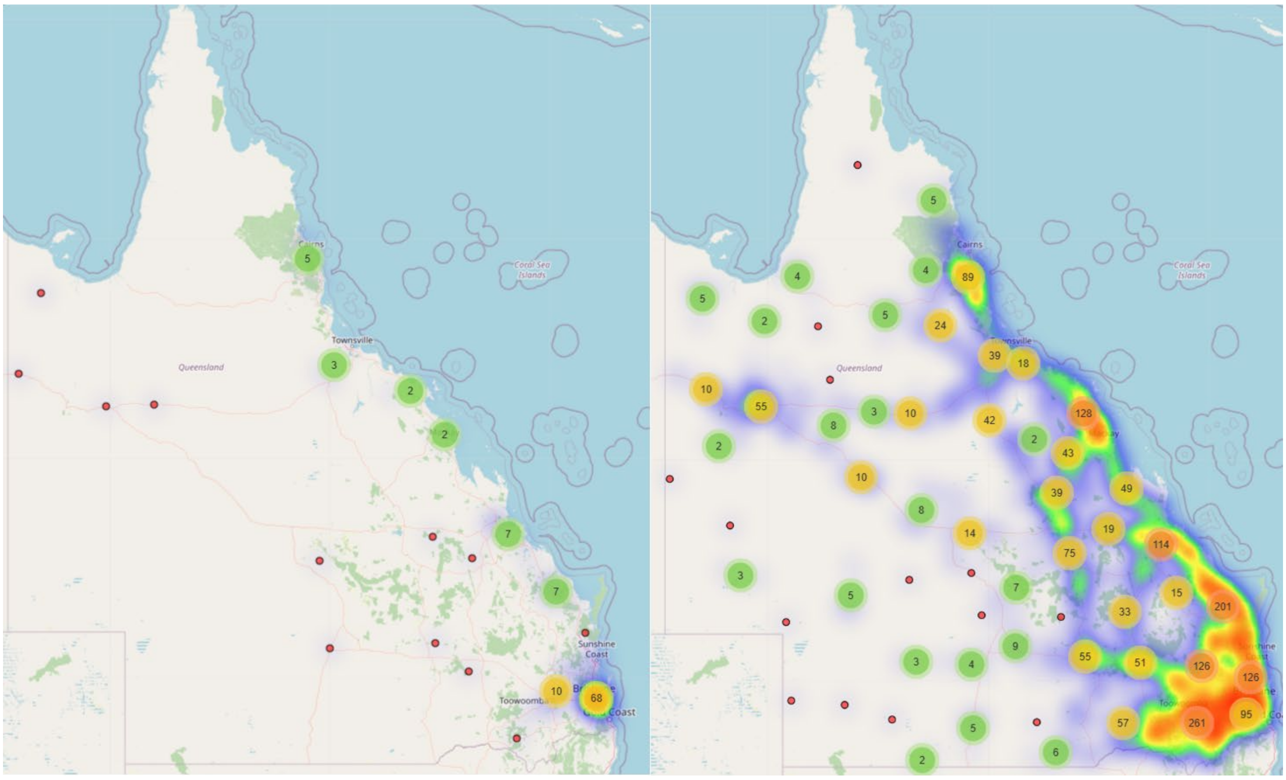

Figure 8 Comparison of 'Truck' rollover events recorded in Queensland in (a) 0-50km/h and (b) 100-110km/h speed zones from 2001-2024

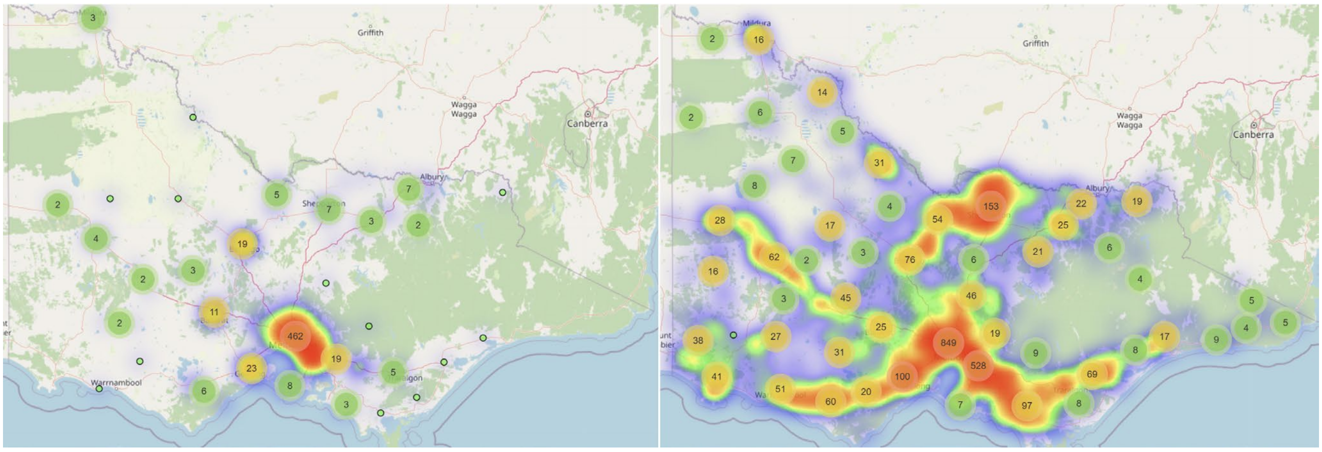

Figure 9 Comparison of heavy vehicle rollover events recorded in Victoria in (a) 50km/h and (b) 100km/h speed zones from 2012-2025

1.3.7 Stability Control Technology

When the PBS scheme was first introduced, it was largely based on research conducted during the 1990s and early 2000s, with the influential 2002 fleet study of 139 indicative vehicles forming some of the most up-to-date data considered. At the time, active vehicle stability systems were largely unavailable, less advanced, and only minimally represented within the fleet. Since then, the adoption of stability control technology in heavy vehicles has grown significantly, supported by requirements under the Australian Design Rules (ADR). Today, the primary systems in use are Electronic Stability Control (ESC) and Roll Stability Control (RSC). While these systems are sometimes referred to using different acronyms, ESC and RSC will be used in this document.

RSC is a driver assistance technology designed to help prevent vehicle rollovers. It operates by utilising data from various vehicle systems and sensors to identify the risk of a rollover and automatically applying braking to reduce speed and enhance stability. Contemporary RSC systems are available for heavy trucks, buses, and trailers.

ESC is a driver assistance technology designed to improve the directional stability of a vehicle. It achieves this by individually controlling the braking of the left and right wheels on each axle to create a corrective yaw moment, aligning the vehicle's behaviour with the driver’s steering input. Additionally, ESC systems often integrate RSC features to stabilise the vehicle when a rollover risk is detected. Currently ESC systems are manufactured for heavy trucks, buses, and trailers.

Stability control technology and the PBS SRT standard share a common objective of reducing the risk of vehicle rollover. However, since ESC/RSC systems are only activated during dynamic manoeuvres, they do not impact a vehicle’s performance under the SRT standard, which is assessed through a static or quasi-steady test. ESC/RSC also has the potential to mitigate some of the risks targeted by the RA and HSTO standards. Evasive manoeuvres, such as those replicated in the test procedures for these standards, generate significant lateral acceleration on the vehicle, particularly on the rear units. This lateral acceleration can trigger ESC/RSC functionalities on vehicle units, enhancing stability during such manoeuvres and improving the performance under the RA and HSTO standards. Despite the widespread adoption of this technology within the PBS fleet, this represents a gap in the current PBS framework, as the Scheme does not currently recognise the benefits that these safety technologies offer in mitigating rollover risk and improving high-speed dynamic stability.

The need for the PBS scheme to recognise the safety improvement afforded by ESC/RSC technology has been emphasised in recent reviews of the current scheme. At the 11th Heavy Vehicle Transport & Technology (HVTT) forum in 2010, Coleman published a paper finding that ESC/RSC were more effective at reducing rollover than setting a minimum SRT of 0.35g and recommended a minimum SRT of 0.335g for tankers and buses and an SRT of 0.28g for all other vehicles that were fitted with a compliant RSC system (Coleman 2010). This paper conducted some numerical modelling, though primarily relied upon the aforementioned TERNZ study which quantified relative crash risk (RCR) to undergird its argument. Later, the NTC released a discussion paper in 2017 identifying a key improvement opportunity to review the PBS technical standards and give flexibility to industry to use technology to comply with safety standards (NTC 2017).

Edition 3 of Technical Advisory Procedure Stability Control for Trucks and Trailers, released in September 2024 by the Australian Trucking Association (ATA) and Industry Technical Council (ITC), detailed the current state of ESC/RSC technology in Australia (ATA 2024). This edition detailed ADR38/05, making it mandatory for trailer brake systems to include RSC from 1 November 2019, and decisions by state governments to mandate the technology. Notably, in the Victorian logging industry there averaged 40 rollovers per year from 2006-2009, which was reduced to zero for B-

Doubles that adopted the technology. In a Technical Bulletin released by the ATA-ITC, they stated that whilst ADR38/05 did not mandate Antilock Braking System (ABS) and roll stability for converter dollies, they would recommend the fitment of a Trailer Electronic Braking System (TEBS) (ATA 2020).

While many modern stability technologies are proprietary and can prove challenging to model, several studies have been successful in modelling ESC/RSC and demonstrating improved vehicle performance through computational simulations. For instance, a paper as part of the NHTSA's study of ESC systems (Chandrasekharan 2007) detailed the development of a software-in-the-loop simulation, by developing both ESC and RSC for the vehicle and then testing it on the J-Turn, slowly increasing steer and fish-hook manoeuvres, it showed that ESC/RSC were effective in quickly identifying rollover risk and applying the brakes. The University of Michigan Transportation Research Institute (UMTRI) developed a hardware-in-the-loop simulation to simulate separate units in a combination, capable of wireless communication, to help develop an algorithm for improving the stability of multi-unit combination heavy vehicles (Pape et al. 2011). The research ran simulations of the lane change and exit ramp manoeuvres and found the ESC system developed was able to detect and apply brakes in situations where the vehicle would otherwise rollover, as demonstrated in Figure 10, and by further applying the wirelessly connected braking between units the vehicle had significantly improved performance.

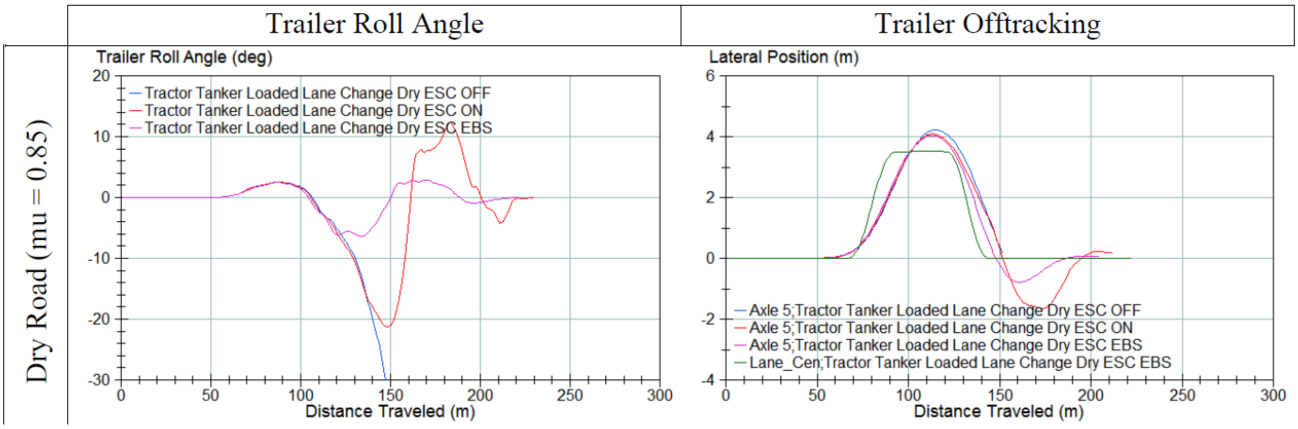

Figure 10 Plots of lane change for a loaded vehicle - roll and tracking errors. (UMTRI U31 Figure 3-48)

The Ford Motor Company released a paper (Ghoneim & Fays 2007) detailing the modelling of their RSC system, built into the existing ESC and ABS modules, incorporating a roll rate sensor and advanced algorithms to detect and mitigate potential rollovers. The model employed a dual-control approach, combining transition control for dynamic manoeuvres (e.g. lane changes) with quasi-steady state feedback control for less dynamic manoeuvres (e.g. J-turns). Within the field of ESC/RSC simulation research, there are manoeuvres that are common across studies, which have shown comparable results highlighting the beneficial impact of this technology on vehicle safety.

Confidence in computer simulation of ESC/RSC has enabled research into potential safety and productivity benefits of this technology. Research such as the study conducted by UMTRI in 2009 (Woodrooffe et al. 2009) was specifically designed to evaluate the safety benefits provided by ESC/RSC for 5-axle tractor semitrailers. The study found RSC was estimated to prevent 3,489 crashes, 106 fatalities, and 4,384 injuries annually, while use of ESC was estimated to prevent 4,659 crashes, 126 fatalities, and 5,909 injuries each year. Collectively, these studies demonstrate that ESC/RSC behaviour can be represented with sufficient fidelity in numerical modelling, indicating that precedence exists for its development and application in support of PBS assessments.

1.3.8 RSC Field-Testing in a PBS Lane Change Manoeuvre

In March 2024, the National Transport Research Organisation (NTRO), as part of the Heavy Vehicle Safety Initiative (HVSI), conducted a field-testing program of Stability Control technologies on long combination vehicles. The testing involved the trailer electronic braking systems (TEBS) with integrated RSC, evaluated using the SAE lane-change manoeuvre on a dynamically sensitive A-Double. The NTRO was subsequently commissioned by the NHVR to develop the outcomes of this research for application to the PBS Scheme in an as-yet unpublished report (Germanchev unpublished 2025). Several of the key findings from literature and claims made in this report are substantiated by the results of the testing done by the NTRO, and the outcomes of this research have contributed to the methodology adopted here.

The A-double was configured for three test cases: "ALL ON", where RSC was enabled for all three trailing units; "ON/OFF/ON", where RSC was enabled for the lead and rear trailers but not the converter dolly; and "ALL OFF", where RSC was disabled for all three trailing units. Preliminary findings from the field testing revealed that enabling RSC produced a significant improvement in both RA and HSTO. The report observed, "Vehicles that failed the RA requirements in simulations were able to pass physical tests when the RSC was turned on, the measured RA values improved from 2.14 (fail) to below 1.9 (pass)". Figure 11 shows the improvement in RA when RSC was enabled. Meanwhile, the HSTO was found to improve by approximately 0.3m when RSC was enabled, as demonstrated in Figure 12.

Figure 11 2024 Anglesea testing RSC All ON vs Dolly OFF vs All OFF RA comparison

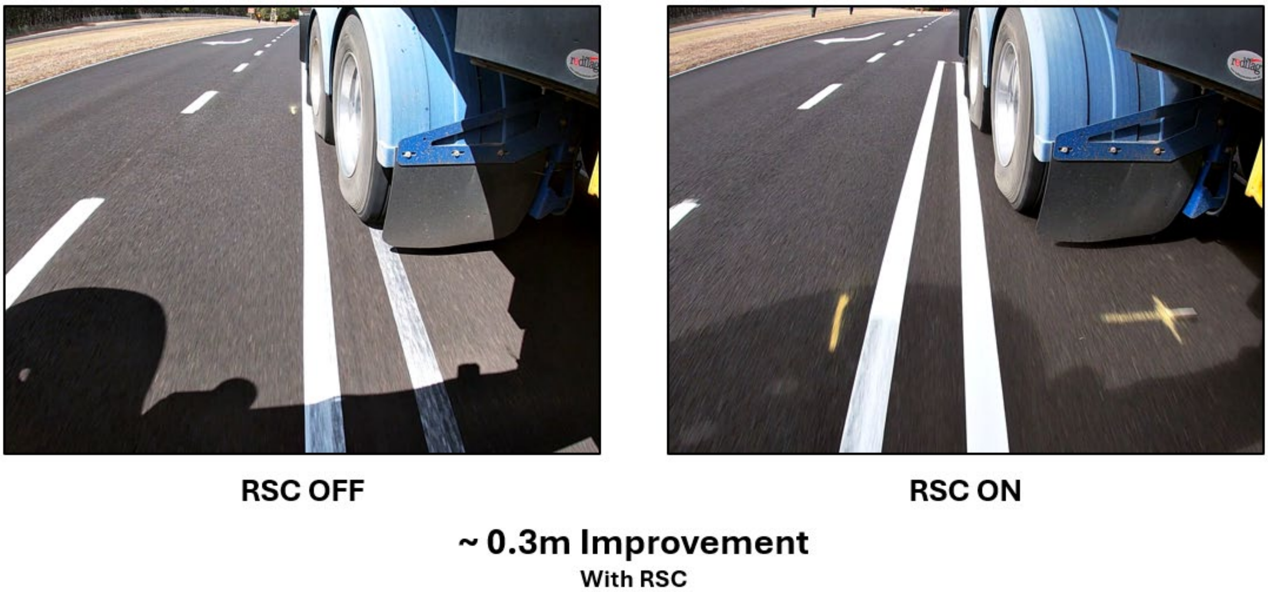

Figure 12 2024 Anglesea testing RSC OFF vs ON HSTO improvement comparison

Despite preliminary findings of an improved RA, those which were calculated from physical testing displayed significant variability between tests and configurations. This is suspected as having several causes, including the influence of braking and the roll damping of the vehicle fitted with RSC which may have temporarily raised the local lateral acceleration while simultaneously controlling the rollover event. Given RSC is designed to reduce lateral acceleration through braking and RA is calculated from the measured lateral acceleration, the NTRO ultimately concluded that RA alone does not fully capture the stability benefit of RSC and an alternative or supplementary measure, such as LTR, should be considered.

NTRO's sensors recorded yaw and roll rates in addition to vehicle speed and lateral acceleration. The yaw rates for two tests are given below (Figure 13). The test observations found that lateral acceleration of the steer axle suffered from a lack of repeatability and the lateral acceleration of the rear trailer was not a reliable indicator of stability except in severe manoeuvres where differences between "ALL ON" and "ALL OFF" configurations become very large. While the rear trailer lateral acceleration only recorded a decrease of 23.8% when RSC was enabled, roll rate and yaw rate were reduced by 71.6% and 61%, respectively. These reductions support the consideration that roll rate and yaw rate are far more robust stability indicators.

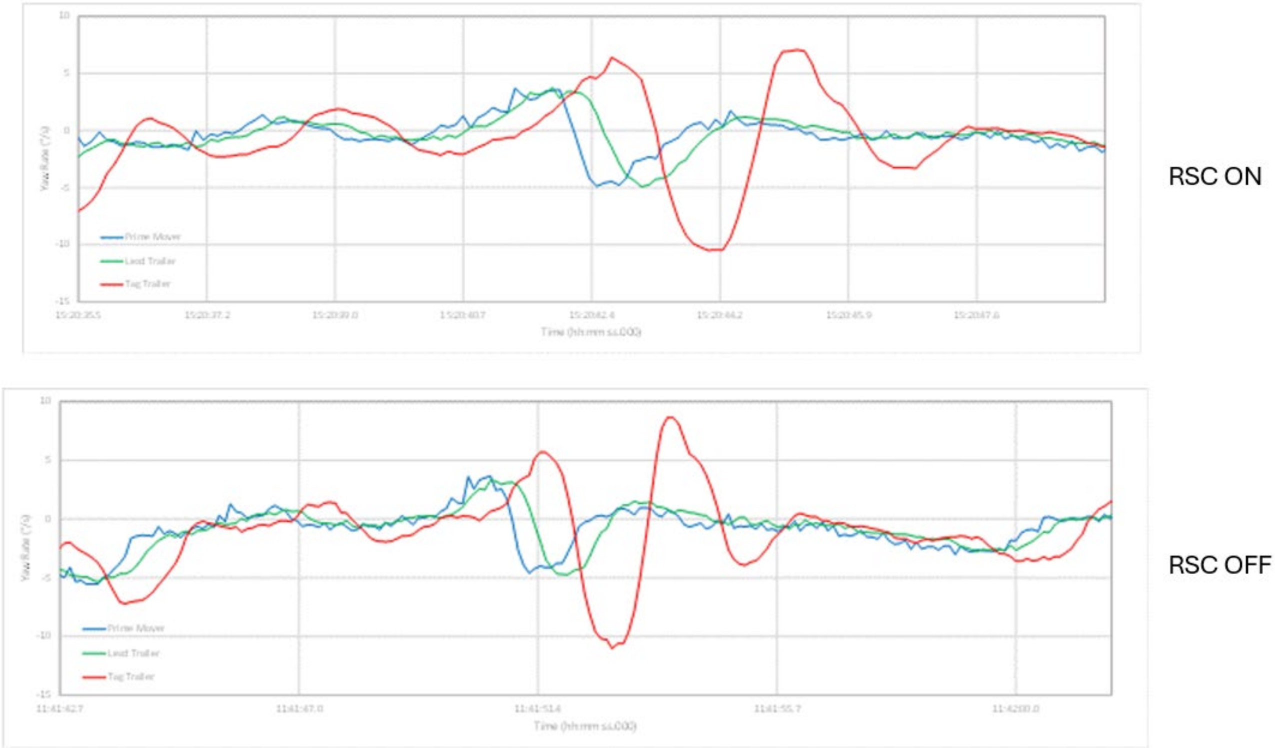

Figure 13 Yaw rates recorded for each vehicle unit from field testing by NTRO.

It became evident during testing that the limits of vehicle stability were not sufficiently breached during the PBS lane change manoeuvre, thus requiring a more severe manoeuvre. Additional tests were performed on the day that fell outside the bounds of the prescribed PBS lane change; however, as shown in Figure 14, using a manoeuvre after the fashion of a double lane change, which better demonstrated the full capability of RSC.

Figure 5.10: Double-lane change - YawB3 - EBS OFF.

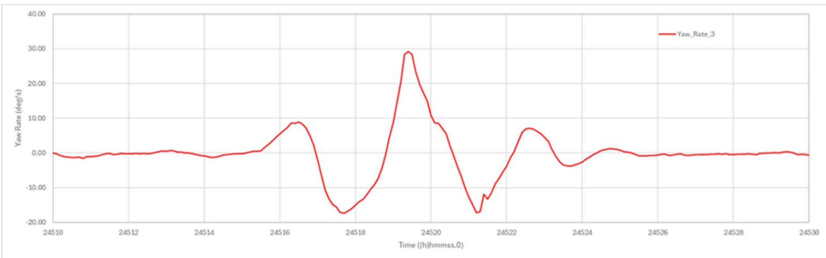

Figure 5.11: Double-lane change - YawB3 - EBS ON.

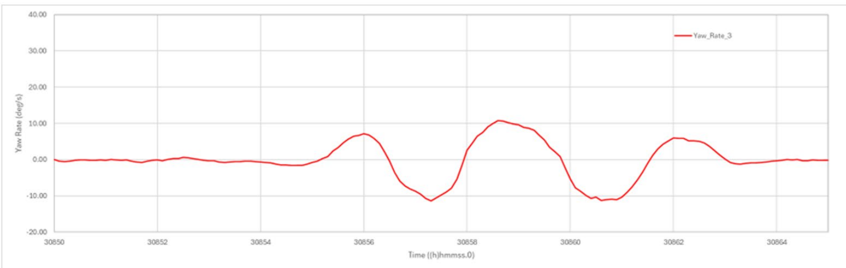

Figure 14 Improvement in yaw rates for double lane change manoeuvre.

The double lane change manoeuvre, as detailed for passenger cars in ISO 3888-1:2018(E), is a manoeuvre whereby the vehicle changes lane twice, with the second lane change returning the vehicle to its original lane. The subsequent vehicle instability caused by negotiating a double lane change manoeuvre exacerbates the observable stability improvements between the various cases “ALL OFF” to “ON/OFF/ON” to “ALL ON”, as demonstrated in Figure 15, where the activation of RSC on the dolly provides additional stability control, preventing rollover. The NTRO recommends the implementation of additional manoeuvres such as a double lane change in conjunction with LTR as a supplementary measure for the inclusion of ESC/RSC into PBS. Additional research would need to be undertaken regarding the suitability and design of a double lane change manoeuvre appropriate to evaluate the Australian heavy vehicle fleet.

Figure 15 Activation of the RSC on the dolly providing additional stability control under an emergency evasive manoeuvre

2 Static Rollover Threshold (SRT)

2.1 SRT Proposed Approach Part I – Alternative Pathway Using Rollover Control Technology

2.1.1 Overview

In recognition of the rollover prevention capability of stability control technology, it is proposed that an alternative performance level for PBS vehicles be introduced. This performance level would require SRT to be within the range of 0.35g > SRT ≥ 0.32g for combinations that have this technology fitted on all units. To provide assurance that the rollover performance of these vehicles is equivalent to that currently required by the PBS Scheme, a supplementary test procedure will be introduced and will be mandatory for the 0.35g > SRT ≥ 0.32g performance level. The purpose of the supplementary test is to ensure that rollover tendency is equivalent (or superior) to that of a vehicle without the technology that has an SRT of 0.35g. Preliminary concept development has used both a constant-radius turn and a more severe manoeuvre as the supplementary test; however, further refinement of these tests will be conducted for implementation.

The alternative SRT performance level of 0.35g > SRT ≥ 0.32g (where fitted with RSC or ESC) aligns with the 0.32g SRT limit originally suggested as the appropriate limit for PBS vehicles by the NRTC (1999).

Since 2008, roughly 8000 PBS Design Approvals have been issued. Of these, only a handful were approved based on physical testing. Simulation and numerical modelling are the preferred methods of performance assessment. Since there are no nationally or internationally recognised standard methods for modelling stability control technology within a PBS context, the NHVR has worked to produce a methodology for simulating this technology that would be appropriate for application to PBS performance assessments. A proof-of-concept of this methodology was achieved with details provided in Section 2.1.2. Further work is required to refine this methodology in preparation for implementation, but the intention is that the Scheme would be updated to include guidance on how the technology is to be modelled.

It is expected that the changes in this proposal will modernise the SRT standard for vehicles fitted with technology, increasing productivity and allowing for greater uptake of the scheme. PBS vehicles have repeatedly been shown to have improved safety outcomes than the conventional fleet and this is due to the broad range of standards that PBS vehicles are required to meet (not just the SRT standard). Therefore, allowing more vehicles into the PBS Scheme should have a net safety benefit for Australia’s heavy vehicle fleet in addition to the associated productivity gains.

The current SRT standard is often the limiting standard when determining the allowable payload height for a vehicle design. Therefore, an alternative stability performance pathway for assessment of vehicles fitted with stability control technology is likely to result in significant productivity improvements via increased payload. In turn, the proposed change is also likely to expected to see retrofitment of the technology to existing PBS vehicles.

2.1.2 Modelling Proof of Concept

Due to the increasing prevalence of simulation in the evaluation of heavy vehicle performance, it is necessary to be able to simulate ESC/RSC to appropriately determine the rollover performance of vehicles fitted with these technologies. As part of assessing a revised performance level for vehicles fitted with rollover control technology, a proof-of-concept RSC (being the comparative worst-case) model needed to be produced. This model, when integrated with existing modelling capabilities, would facilitate rapid simulation of the impacts of the system on the dynamic stability performance of a wide range of vehicle types through various manoeuvres, in a way that a statically determined model cannot.

This model was developed to establish an appropriate basis for simulating RSC behaviour to support the proposed PBS Phase 4 dynamic stability standard improvements. Its development focused on replicating the general response characteristics of commercially available systems, using a combination of experimental data, industry consultation, and validation against physical and simulation test results.

A key challenge in this work is that the detailed implementation parameters are not generally available in a form that can be readily embedded into PBS simulations. Various manufacturers use their own control structures, inputs and thresholds to determine response tailored to specific vehicle platforms. The NHVR, in consultation with system suppliers and PBS Assessors, will work towards developing a generic simulation methodology that could be used in vehicle assessments. Nevertheless, the NHVR has successfully developed a partially validated proof-of-concept model, based on research and physical testing, which captures the typical RSC response.

To support the development of this model, consultations were held with representatives from major system suppliers. These discussions provided valuable insight into the general operating principles of each system and the operational approach to interpreting dynamic response and intervention. The controller was configured so that roll control, rather than yaw instability, was the main priority, which is reflected in the simulation results where lateral acceleration and LTR responses exhibit high sensitivity.

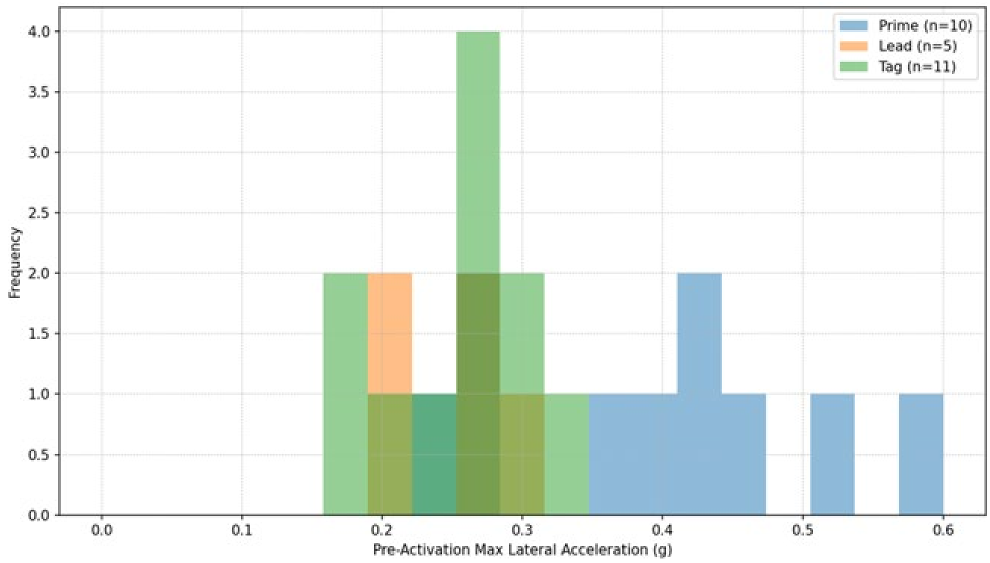

Figure 16 Histogram of the pre-activation lateral accelerations for the prime, lead and tag trailers (source: NTRO, 2025)

The aforementioned research commissioned by the NHVR from the NTRO (Germanchev unpublished), provided valuable insight whereby lateral acceleration was observed as a primary trigger for RSC intervention. It was observed that the range at which the ESC responded to the experienced lateral acceleration of the vehicle unit varies under an approximate normal distribution about 0.15g – 0.6g (Figure 16). This demonstrated that there is an additional, and significant, contributing factor influencing the operation of the system beyond that of the magnitude of lateral acceleration in isolation.

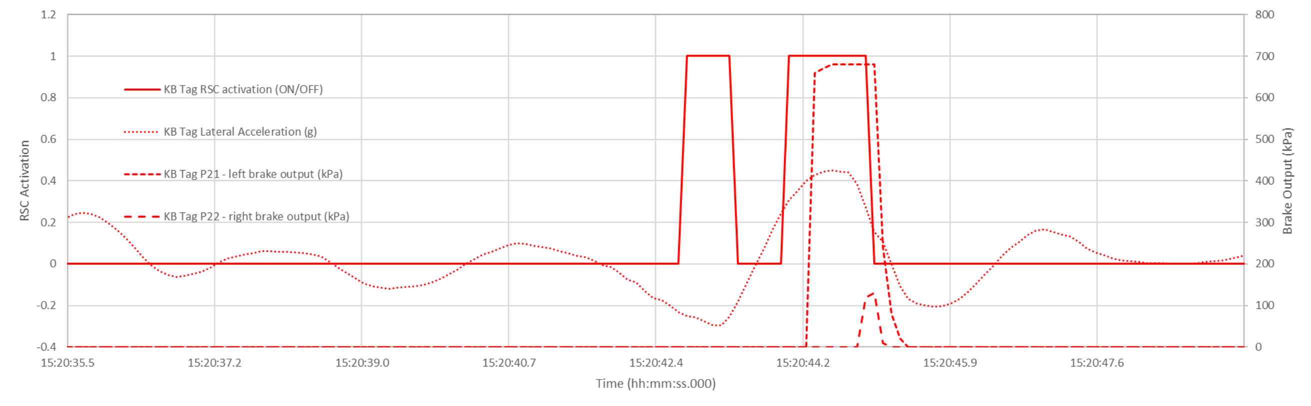

Figure 17 RSC activation, lateral acceleration, and braking pressure (Germanchev unpublished)

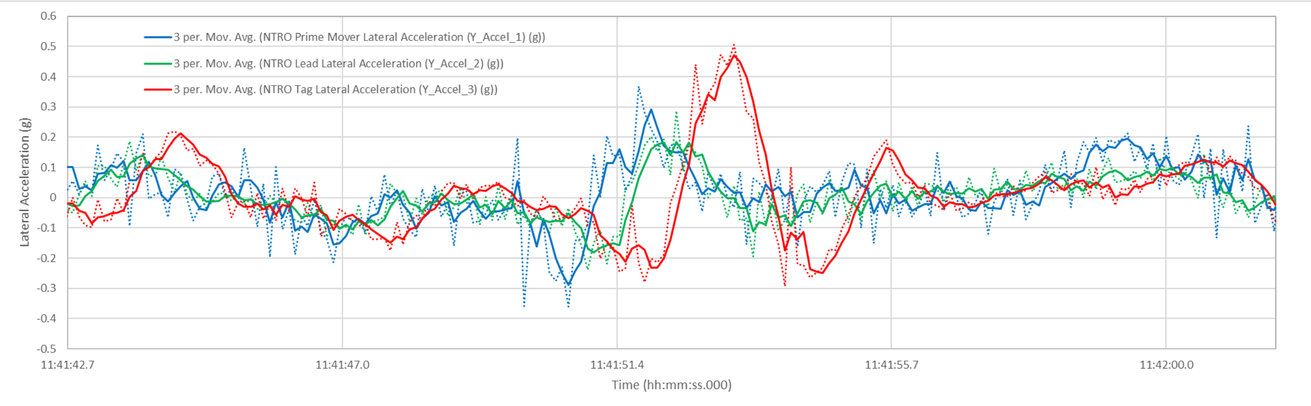

Figure 18 Prime mover, lead trailer, and rear trailer lateral acceleration comparison (Germanchev unpublished)

The NTRO's research further evaluated the activation thresholds of an RSC system from field testing data conducted with the NHVR in 2024. Analysis of the brake activation signal (Figure 17) relative to measured lateral acceleration (Figure 18),indicated that the RSC generally begins building brake pressure when lateral acceleration exceeds ~0.2g in magnitude and begins to reduce brake pressure once it falls back below ~0.3g, with jerk apparently considered as a factor of the strength of brake pressure response. These findings informed the calibration of the proof-of-concept model for cross reference of its outputs against the Anglesea testing data.

As part of the research to develop a hardware-in-the-loop simulation for ESC and EBS on heavy vehicles, UMTRI (Pape et al. 2011) found "any attempt to manage yaw instability will have to manage a much larger set of driving situations as compared to roll instability." Further, it concluded that roll instability is primarily related excessive lateral acceleration while yaw instability is that of both lateral acceleration and vehicle speed. Purportedly, this instability can be observed at lateral accelerations as low as 0.1g. The authors observe that, "Woodrooffe and Blower (2010) noted that adding ESC improved roll stability and concluded that the added roll benefit came from the yaw controller activating before the roll controller, producing a restorative response before the activation of the roll controller."

Andersky and Conklin (2008 in U31 UMTRI 2008) provided an explanation for this behaviour in this way,

> *"By helping a vehicle maintain directional stability during both oversteer and understeer situations, the driver's intended path continues to be followed, and loss-of-control situations are minimized [sic]. Many rollovers are the outcome of loss-of-control situations that begin when the driver manoeuvres to avoid a situation – which, in turn, initiates directional instability – leading to the eventual lateral acceleration event culminating in the rollover."*

Importantly, yaw control was not incorporated into the proof-of-concept, as demonstrated in the modest impact on HSTO results; yaw instability is a more complex control problem than roll instability. Incorporating yaw response would likely produce improved HSTO performance from the application of the controller however, the proof-of-concept was deemed as a rudimentary “worst-case” response without consideration to yaw.

Instead, the controller operated using a state-based two-tiered approach using both the magnitude of lateral acceleration and jerk. This was compared against the braking outputs from the physical testing using the same lateral acceleration input data. The simulated brake responses to the recorded brake activation patterns from the real-world testing, the model was verified to produce similar pressure building and decay characteristics. This provided confidence that the model adequately replicated the general behaviour of RSC under the represented conditions.

Although the model performed well when validating against the available data, it remains a proof of concept and includes several simplifications and assumptions. Such as, it assumes that the brakes are primarily on or off, with a preset delay to reach full braking pressure. This does not account for braking pressure application/loss rates as well as the complexities of pneumatic brake system pressure travel. Further work is expected to enable refinement of the model and improved accuracy in future simulations.

The insights gained from this work provide a strong foundation for future refinement and for extending the simulation framework to include more advanced stability control logic. This model has allowed for the collection of simulation data necessary in supporting the coming SRT, HSTO, and RA Sections of this report.

2.1.3 Supplementary Comparative Test Procedure Selection

Whilst SRT is a valuable metric for assessing the stability of a vehicle, it does not capture all aspects of stability and resistance to rollover. Systems such as RSC/ESC cannot be tested in a static environment and as such alternative dynamic tests are needed to fully understand their benefits.

The current PBS standard permits two testing options, a tilt table test where the vehicle rests on a platform and is slowly tilted sideways until wheel liftoff occurs on the uphill side, or a constant radius quasi-steady turn, where the vehicle’s speed is slowly increased until the point of rollover instability is reached. In both cases, the lateral acceleration is measured and used to determine the SRT performance value

A recently performed study on heavy truck accidents, based on the Large Truck Crash Causation Study (LTCCS), set out to develop a test manoeuvre for the evaluation of yaw stability (Kharrazi and Thomson, 2008). One of the key findings of the study was that negotiating a curve was found to be the critical manoeuvre overwhelmingly represented in 59.39% of crashes due to loss of control and 35.5% of crashes due to only yaw instability (Figure 19).

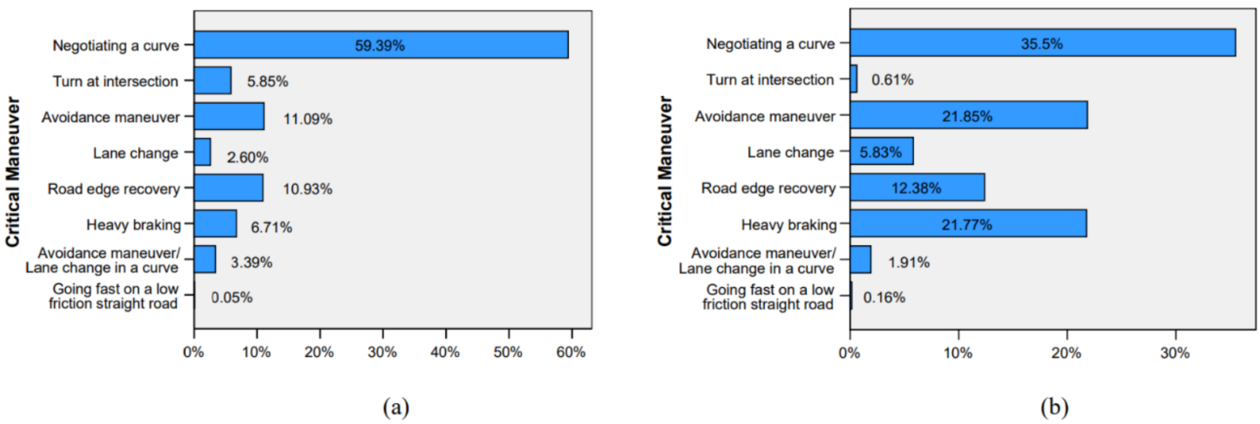

Figure 19 (a) Critical manoeuvre for trucks with loss of control (b) Critical manoeuvre for trucks with only yaw instability (Kharrazi and Thomson 2008)

Whilst the existing tests adequately assesses lateral stability in most situations, evaluation of yaw stability would require a dynamic test. To assist in the assessment of RSC/ESC, it was decided to include assessment of vehicles with alternative SRT values on two additional road profiles. Initial designs of these road profiles were developed to induce both a high change in lateral acceleration which is common on the entrance to a roundabout (roundabout test track), as well as a second profile designed to induce a pseudo steady state lateral acceleration (J-entry to transient curve test track) as shown in Figure .

These profiles, like the others used in the PBS standards such as the lane change used for HSTO and RA assessments, are used for comparative and indicative-benchmarking purposes.

A visual description of the roundabout and J-entry to transient curve test tracks can be seen in Figure 20. In a similar vein to the transient curve test to measure the SRT of a vehicle by inducing a sustained lateral acceleration response, the J-entry to transient curve test attempts to induce a similar sustained pattern, except for the entryway. This test is intended to be run at higher speeds than the roundabout test and considers the stability controller's response to a linear entry into a sustained turn. Unlike the roundabout test which includes changing adverse crossfall to replicate real world conditions, this track is wholly flat.

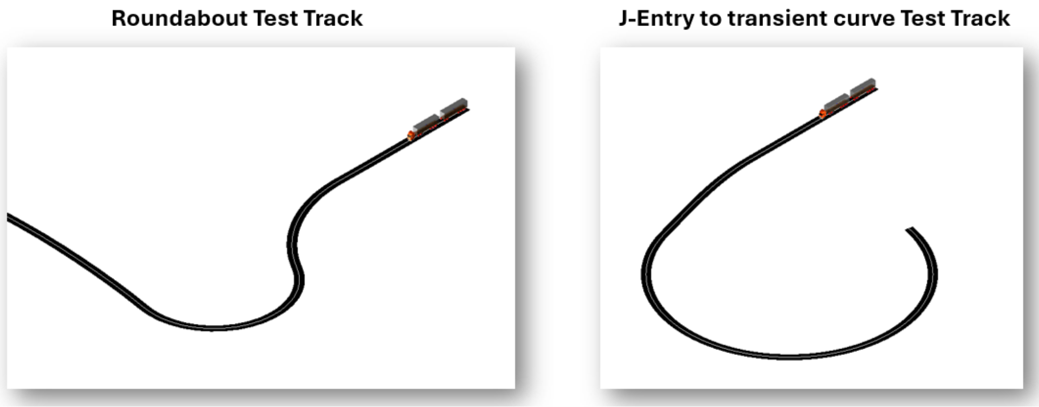

Figure 20 Road profiles used for SRT simulations

It is proposed that where a 0.35g > SRT ≥ 0.32g vehicle, fitted with technology, can successfully negotiate the road profiles beyond the maximum speed whereby a 0.35g SRT vehicle, without technology, cannot then it will be considered equivalent for the purposes of SRT assessment.

The profiles that have been used in this report are proof-of-concept designs only and require further investigation and refinement before implementation of these standards. Further clarification of the test via comparison vehicle, entry speed or similar will be provided during the implementation phase of this project.

2.1.4 Comparative Testing

For the comparative dynamic SRT testing that has been performed in this report, an A-double and a prime mover semitrailer combination were selected for detailed comparison below. A single-entry speed for each combination type was chosen based on a 0.35g SRT combination without ESC or RSC inducing a rollover event. For the prime mover semitrailer combination, an additional 0.37g SRT variant was also assessed. The comparative 0.32g SRT combination was then simulated with RSC at the same entry speed that resulted in the 0.35g SRT vehicle rolling. LTR, lateral acceleration, and vehicle speed were recorded for each different combination and configuration.

Tests conducted using the roundabout test track assessed eleven combinations with SRTs ranging from 0.35g to 0.44g. All unassisted combinations experienced a rollover event at speeds less than 42km/h. Combinations included:

- Prime Mover Semi
- Truck and Dog
- B-double
- A-Double
- B-Triple
- AB- Triple
- A-Triple

For the J-entry to transient curve test track, an entry speed was chosen based on a 0.35g SRT combination without ESC or RSC inducing a rollover event. As above, another 0.37g SRT variant of the prime mover semitrailer combination was also assessed. The comparative 0.32g SRT combination was then simulated with RSC and the same entry speed that resulted in the 0.35g SRT vehicle rolling. LTR, lateral acceleration, and vehicle speed were recorded for each different combination and configuration.

2.1.5 Simulations Using Stability Control Technology

Comparisons of the prime mover semitrailer and A-double combination of varying SRT values negotiating different tests tracks at the same entry speeds were selected for analysis below. Demonstrated in Figure 21, beginning at the same entry speeds, 0.32g SRT vehicles equipped with RSC safely negotiated the test tracks, while 0.35g SRT vehicles were unable to and experienced rollovers. This clearly demonstrates that the RSC intervention provided a sufficient performance improvement as compared to the PBS compliant combinations (0.35g SRT or above). Note that whilst LTR is represented in results of this study as individual units and not roll-coupled units, this was intentional for clarity in analysing the dynamic response of the individual vehicle units.

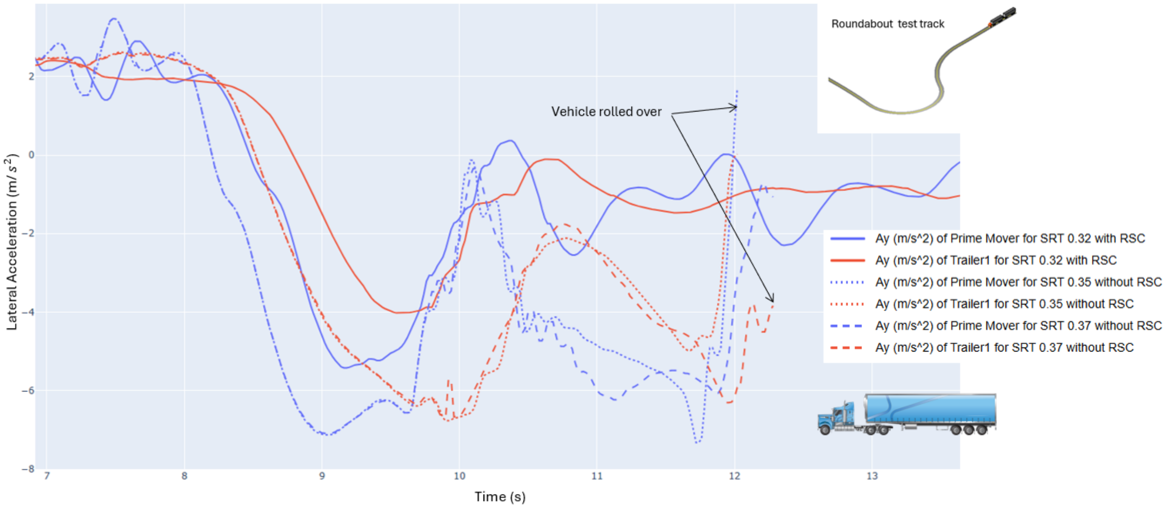

Figure 21 Lateral acceleration of prime mover semitrailer at roundabout test track showing effectiveness of RSC

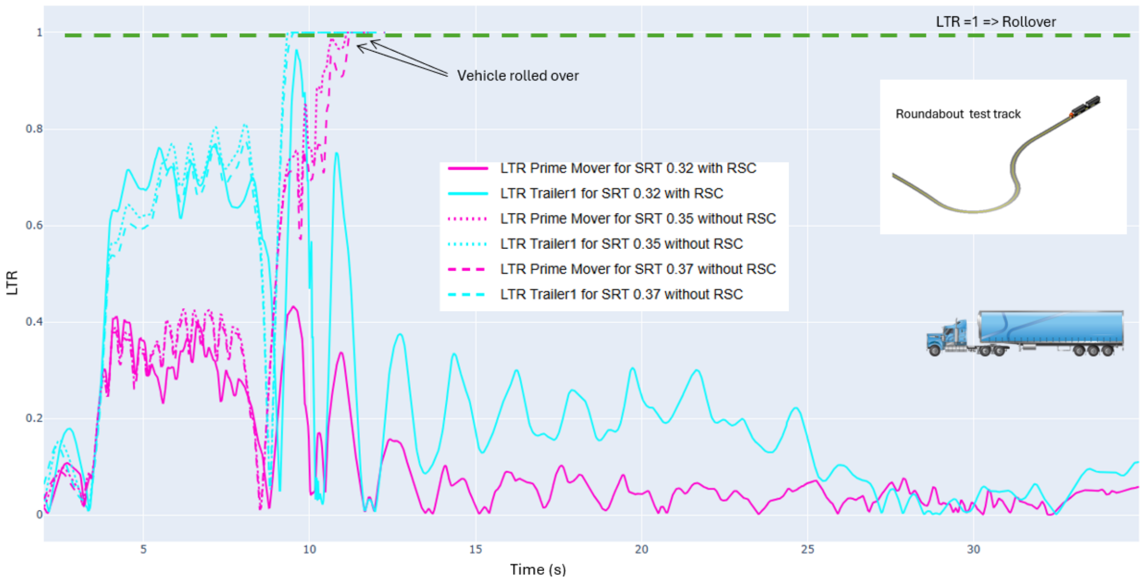

Figure 22 LTR of prime mover semitrailer at roundabout test track showing effectiveness of RSC

Comparisons of the LTR for multiple SRT prime mover semitrailer combinations (Figure 22) show that 0.35g and 0.37g SRT vehicles without RSC, experienced a rapid buildup to the trailer's lateral acceleration (demonstrating a significantly higher jerk) upon entering the roundabout's peak. Both the magnitude of the acceleration as well as the sharpness of the peak in those combinations showed an unstable response to the dynamic manoeuvre progressing into an uncontrolled roll. By contrast, the 0.32g vehicle equipped with RSC showed a damped gradual rise in lateral acceleration, with a limited peak magnitude, quickly returning towards neutral under braking, thereby preventing an escalation of instability.

The LTR measurement reinforces this observation, where the PBS compliant cases without stability technology exhibited sharp rises to 1.0 and a sustained presence at the rollover boundary. Conversely, the combination which was equipped with RSC at a lower SRT value showed a controlled response, with a notable difference between the LTR of the prime mover as compared to its trailer (Figure 21Figure 24). Hence demonstrating something akin to a dynamic-pause in roll-coupling, as the trailer exhibited a far greater LTR than the hauling unit in this case due to braking. Whereas in the non-technology cases, the roll coupling was maintained such that both front and rear units produced similar traces of LTR with the prime mover following its semitrailer to the boundary of LTR in an uncontrolled manner (Figure 22).

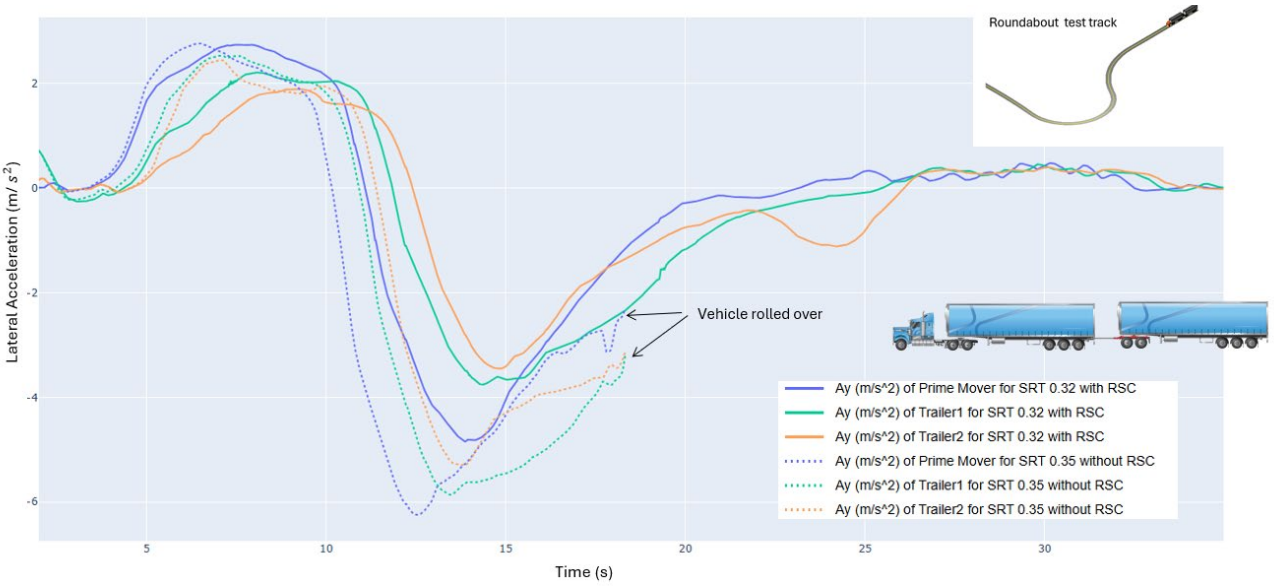

Figure 23 Lateral acceleration of A-double at roundabout test track showing effectiveness of RSC

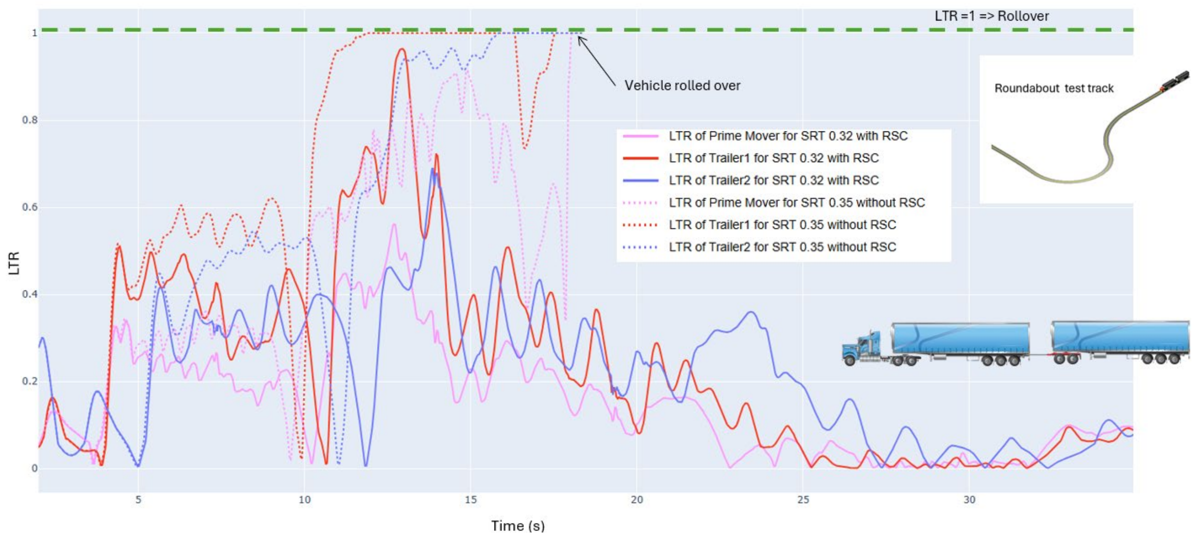

Figure 24 LTR of A-double at roundabout test track showing effectiveness of RSC

In simulated testing on an adverse real-world roundabout track, the lateral acceleration showed significant instabilities prior to roll-over for the PBS compliant 0.35g SRT A-double which was not equipped with RSC. Conversely, the lower SRT vehicle (0.32g SRT) equipped with rollover stability technology completed the manoeuvre by controlling potential 'runaway' shifts in felt lateral acceleration (Figure 23Figure 25).

As the vehicle approaches the peak of the turn, having substantially shifted its load from one side to the other, the RSC model applies brake interventions in response to both the magnitude of the lateral acceleration and the rate of change of the lateral acceleration (jerk). Similarly, the LTR showed significant shifts in response to the extremities of the felt lateral acceleration rapidly reaching a higher magnitude of about 6m/s^2, as compared to the 5m/s^2 or less in the vehicle with an SRT of 0.32g and RSC (Figure 24). When using the roll stability control proof-of-concept module, the combination with a 0.35g SRT performed worse compared 0.32g SRT vehicles equipped with stability technology when under a demanding low speed dynamic manoeuvre.

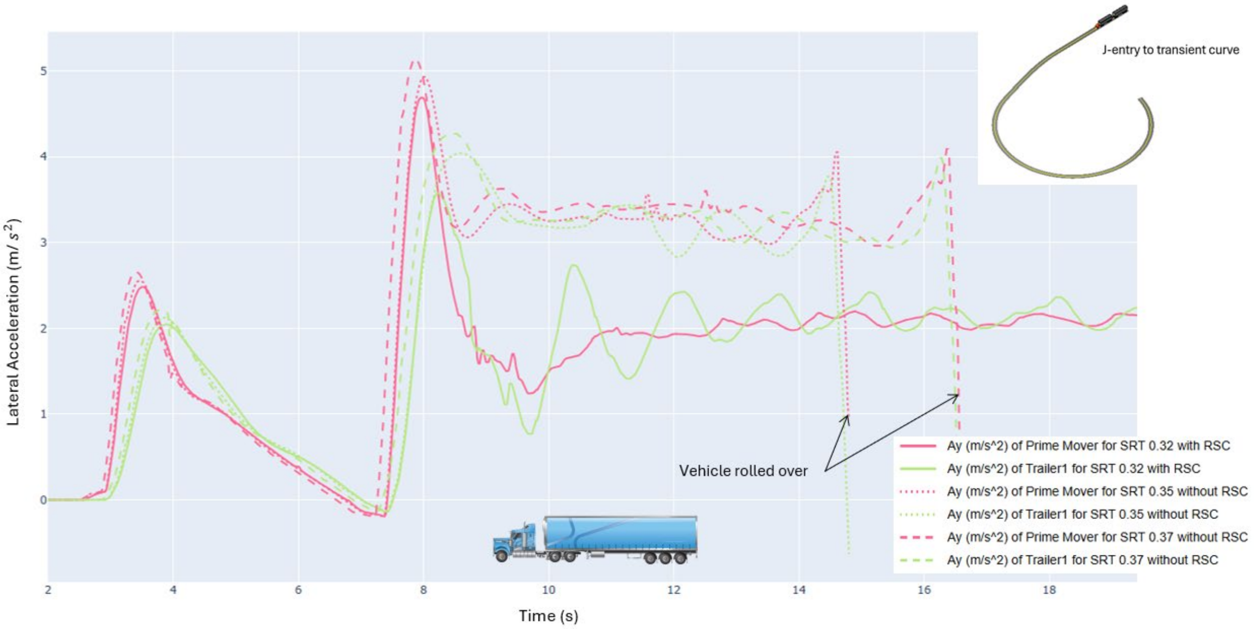

Figure 25 Lateral acceleration of prime mover semitrailer at J-entry to transient curve test track showing effectiveness of RSC

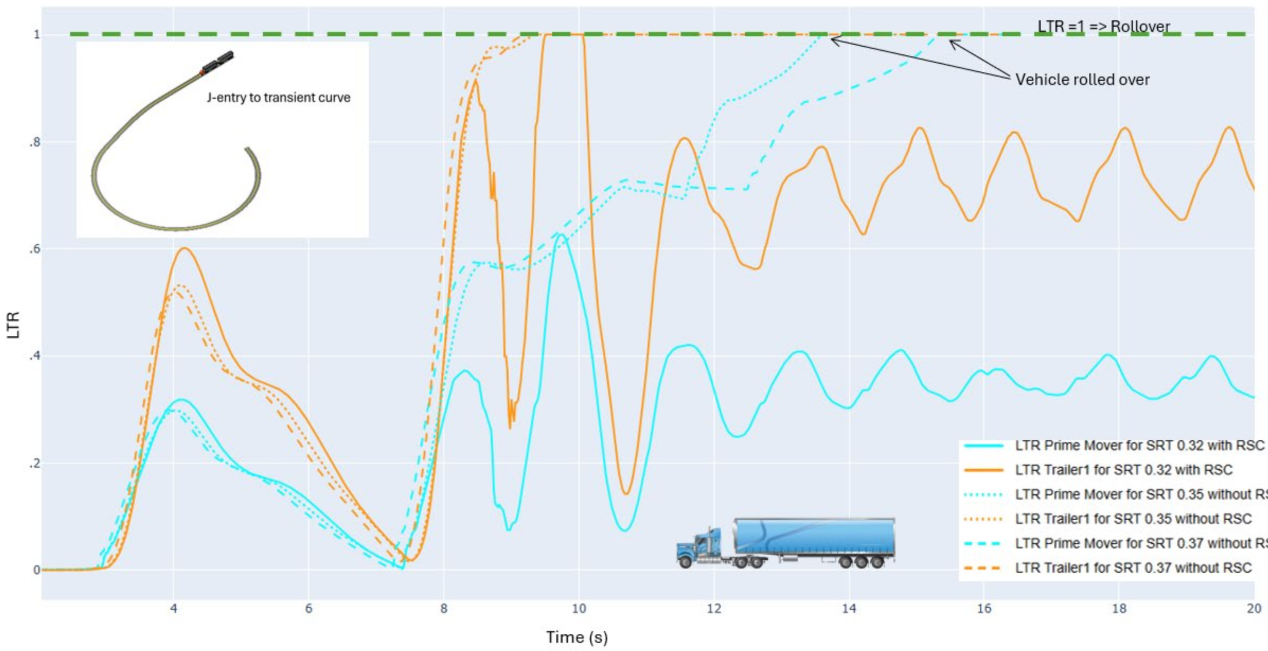

Figure 26 LTR of prime mover semitrailer at J-entry to transient curve test track showing effectiveness of RSC

Similarly, the prime mover semitrailer combinations without stability control showed the same fundamental problem as the A-double, though without the additional trailer (Figure 25). As the vehicle transitions from the J-entry into the steady curve, the trailer lateral acceleration sharply spikes to approximately 5m/s^2 for both the 0.35g and 0.37g cases. Both cases without RSC demonstrated the roll-coupling with the prime mover which followed the high jerk rate of the semitrailer and subsequently experienced a lateral acceleration above 4m/s^2. Both cases exhibited a sustained high lateral acceleration for the subsequent five seconds, progressing toward an unstable rollover event.

However, the vehicle operating at a lower SRT of 0.32g showed the indicative performance improvement provided by the RSC module which controlled the peak lateral acceleration and the jerk. The technology controlled the vehicle, even when the trailer experienced an undesirable LTR at the threshold about the 10-second mark (Figure 26). The rate of change of the lateral acceleration was muted from a potential roll build up through the activation of the RSC unit. Both reducing the dwell time of the trailer at the LTR boundary and damping the excitation of the prime mover's LTR change. The subsequent oscillations of the combination show moderated decaying response to the entry event as the vehicle settled into the transient turn with a felt lateral acceleration about 2m/s^2.

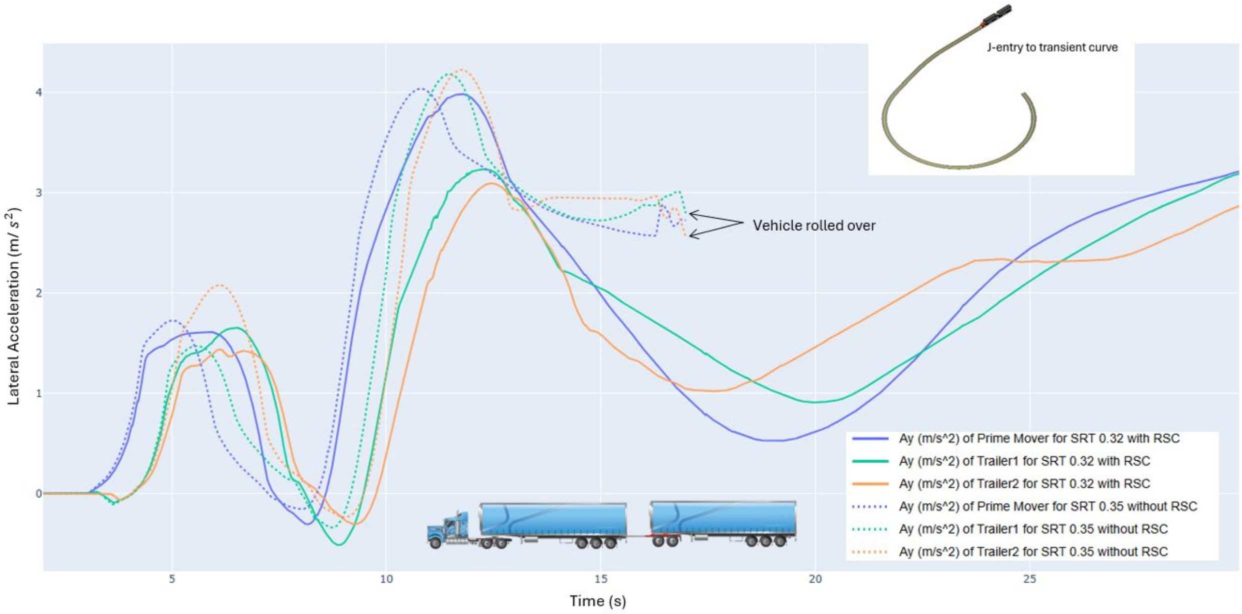

Figure 27 Lateral acceleration of A-double at J-entry to transient curve test track showing effectiveness of RSC

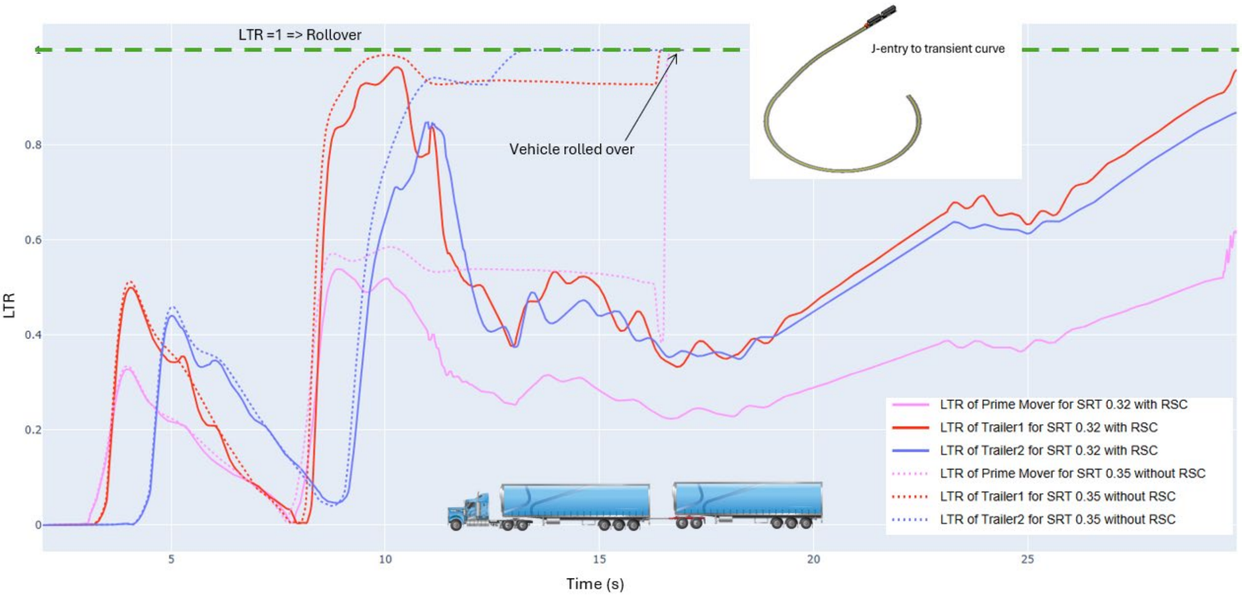

Figure 28 LTR of A-double at J-entry to transient curve test track showing effectiveness of RSC

For the A-double undertaking the transient curve manoeuvre, the case at 0.35g SRT with no stability technology enabled experienced a sharp rate of change of the lateral acceleration as the vehicle transitioned from the J-entry nine seconds into the test (Figure 27 and Figure 28). This resulted in a steep climb of the LTR towards the boundary threshold and a sustained load transfer in the 0.95 to 1.0 range for the two rear trailers. While the lateral acceleration began to reduce from the peak of ~4m/s^2 and stabilise about the 3m/s^2 mark; the transient induced acceleration at this point, combined with the load transfer almost exclusively to one side induced rollover. Firstly, in the front trailer, followed by the rear trailer, then the vehicle whole.

For the 0.32g SRT vehicle equipped with RSC, while experiencing similar magnitude of lateral acceleration on the prime mover (Figure 25 and Figure 26), the total peak lateral acceleration for the trailers was controlled by braking, maintaining a peak just above 3m/s^2, and restricting the duration at which the LTR dwells near the 1.0 boundary (Figure 28). The total peak to peak lateral acceleration when controlled with RSC is significantly less, and the rate of change trends downwards in response to the braking effort by the unit.

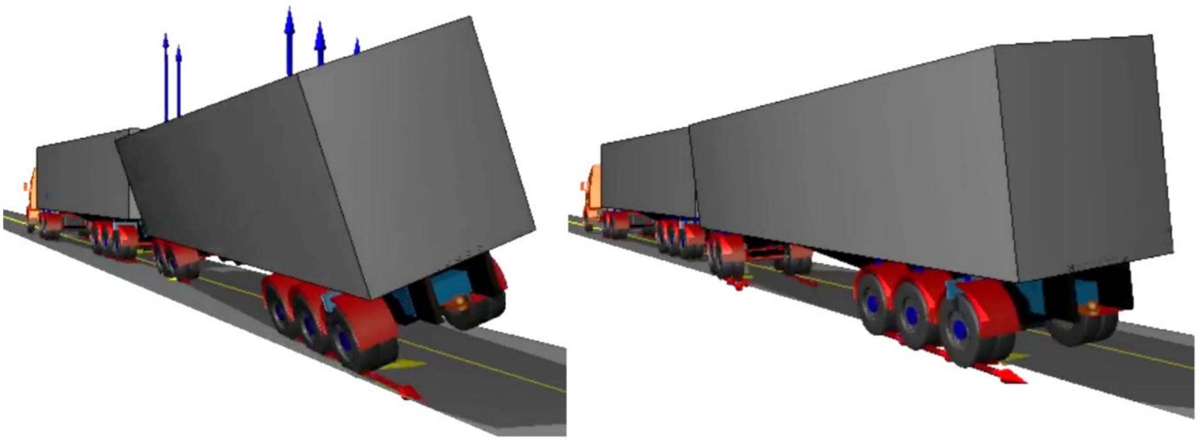

Figure 29 An A-double undertaking a lane change manoeuvre - where both trailers are equipped with RSC on the left, but not on the dolly, versus the trailer and the dolly all fitted with RSC on the right

With consideration of the changes proposed to the high-speed standards and the implementation of the new DSUB standard regarding the fitting of RSC to a converter dolly, additional simulations were conducted on the standard lane change manoeuvre. Figure 29 demonstrates the comparison of RSC not enabled on the dolly (left), in contrast to the exact same combination with RSC enabled on the converter dolly (right). All other aspects were unchanged between the simulations. The dynamic rollover tendency was muted by the activation of the brakes on the dolly in response to the change in lateral acceleration which also demonstrated improved directional stability by the control of the rear trailer unit. Note that in both cases the rear trailer experienced an LTR of 1.0 with wheel lift; something already permissible by current test requirements making use of the lane change manoeuvre. Further reinforcing the need for inclusion of LTR restrictions in assessments to close a previously unaddressed loophole.

As previously stated, a simplified RSC module was developed for modelling and simulation, with more research into this underdeveloped area of dynamic modelling recommended. Notwithstanding, the above clearly demonstrate that, when equipped with RSC technology imposing a brake response according to a vehicle's stability, 0.32g SRT vehicles showed a markedly more controlled response to instability in both transient and adverse conditions as compared to the existing PBS vehicles with a high SRT value without RSC.

2.1.6 Technical Details of Proposal

This alternative assessment pathway for SRT provides another means of compliance to the existing rollover stability standard. This alternative assessment method can enhance the PBS scheme by providing an opportunity to utilise heavy vehicle safety technology. Further, it can also deliver improved on-road performance under dynamic, real-life conditions.

This alternative compliance pathway is applicable only to vehicles that are typically required to meet the 0.35g SRT limit. It does not extend to combinations that are subject to higher SRT requirements under the PBS Assessment Rules such as DG vehicles, buses, and coaches.

It is intended that the NHVR will provide a standardised method of assessing ESC/RSC so that a base level of performance can be established and so the stability control is representative of real-world vehicles without overvaluing the benefits of the systems.

Part of this new standard will require the vehicle combinations to complete the test profile with an LTR of less than 0.9. Whilst examples in this report shows instances of the 0.32g SRT vehicles briefly exceeding this 0.9 LTR limit, the profiles were designed to be extreme tests and were primarily to explore the RSC modelling and response with a proof-of-concept RSC simulation module.

As previously mentioned, it is expected that further development of the test profiles and procedures will be conducted and that further clarification of the test via comparison vehicle, entry speed or similar will be provided during the implementation phase of this project. Hence, as it is proposed below, the test manoeuvre, or manoeuvres, by which this method is evaluated will be the subject of further investigation and as such is simply referred to at this stage as 'the specified manoeuvre'.

The performance levels stated in the supplementary 0.35g > SRT ≥ 0.32g SRT standard will be:

Performance Based Standards Road Class	Performance Level Required
All Levels (For vehicles having an SRT not less than 0.32g and fitted with roll stability control)	Successfully complete the specified manoeuvre with an entry speed as specified utilising RSC and maintain an LTR not greater than 0.9 throughout.

Where this alternative means of compliance, using the additional SRT level of 0.35g > SRT ≥ 0.32g, is utilised, all vehicle units within the combination must be fitted with ESC or RSC.

2.2 SRT Proposed Approach part II - Update Performance Level for DG Vehicles

2.2.1 Overview

Vehicles carrying portable tanks containing dangerous goods are generally not classified as road tank vehicles under the ADG Code (2024). Portable tanks such as ISO tanks are treated distinctly within the Code. However, within PBS, the SRT standard does not provide a specific SRT performance level for vehicles carrying portable tanks. Under a strict reading of the current wording, these vehicles may not be required to 0.4g SRT performance requirement, but rather 0.35g. This ambiguity has caused assessors to apply differing interpretations in practice.

In response to industry enquiries regarding which Dangerous Goods (DG) vehicles must comply with the 0.4g performance level, it is proposed that a definition be added to the document to improve clarity.

2.2.2 Australian Dangerous Goods Code and AS2809 requirements

The ADG Code applies requirements to heavy vehicles transporting dangerous goods on Australian roads. The ADG Code is implemented nationwide, with only minor interpretive variations between the jurisdictions. The PBS Scheme only focusses on requirements for PBS and not requirements within other legislative instruments. Where the SRT standard applies a higher performance level of 0.4g for "road tankers hauling dangerous goods in bulk". The current PBS Rules do not contain any definition for *road tanker* which has resulted in the uncertainty within industry as to which vehicles are subject to the 0.4g performance level.

Both the ADG Code and AS 2809.1 contain stability requirements applicable to road tank vehicles and vehicles carrying portable tanks containing dangerous goods. Firstly, the ADG Code defines a road tank vehicle as, "a road vehicle of which a tank forms part or to which a tank, other than a portable tank, is attached". While AS2809.1 goes further and deems, "conventional vehicles that carry portable or demountable tanks which are filled or discharged while on the vehicle," as road tank vehicles.

There is a cross-reference between the two, where it is a requirement in the ADG Code that dangerous goods must not be transported in a road tank vehicle unless that vehicle conforms with AS 2809 (2023).

That is, for road tank vehicles, AS2809.1 (2023) states:

"(a) For rigid road tank vehicles, designed in accordance with AS 2809.3 and AS 2809.6, the maximum allowable stability angle shall be 64°.

(b) For all other road tank vehicles, portable tanks and demountable tanks the maximum allowable stability angle shall be 62°.

An alternative to Items (a) and (b) would be a static roll-over threshold (SRT) calculation. SRT shall be calculated using the NHVR PBS methodology. The calculated SRT shall equal or exceed 0.4g."

The stability angle methodology is a simplified 2D geometric analysis whereas the PBS SRT assessment is a more comprehensive assessment that considers vehicle characteristics such as suspension specifications. Figure 30 provides a visual of the stability angle referenced in these requirements.

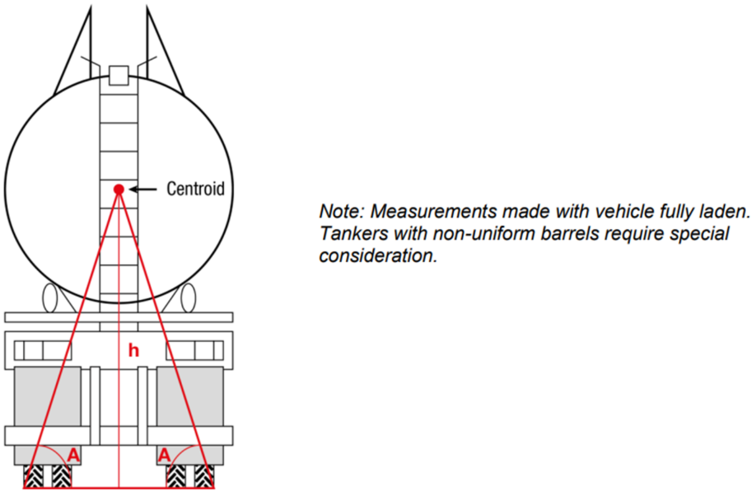

Figure 30 WA DG Safety Guide Road Transport of Dangerous Goods, Stability Drawing

For vehicles carrying portable tanks containing dangerous goods, the ADG code specifies:

"Except when the tank is nominally empty, dangerous goods in the liquid state must not be transported on a road vehicle in a portable tank having a capacity of more than 7,500 litres, unless:

(a) the height of the centroid of the tank cross Section at tank half length falls within an isosceles triangle having:

i. a base length at ground level equal to the overall width between the outside walls of the outside tyres of the main load bearing axle groups, and

ii. base angles not exceeding 64 degrees; or

(b) the distance between the ground and the load bearing surface of the bottom corner casting of the loaded tank does not exceed 1100mm. These stability requirements are unique to portable tanks and are not replicated for other dangerous goods transport."

The NHVR is aware that an update to the ADG Code is currently in progress and as such, certain aspects of the above could be subject to change, particularly around definitions and application of the stability requirements.

An example of a vehicle carrying a portable tank is pictured below.

Figure 31 Portable tanks containing dangerous tanks

Vehicles transporting dangerous goods in tanks must also comply with requirements regarding fill levels. The ADG Code states that tanks with one or more compartments exceeding 8,600 L in capacity must not be filled with a liquid to a degree of filling of more than 15% but less than 80%. It also states that portable tanks containing a liquid are not to have a degree of filling of more than 20% but less than 80% unless the tank is divided by partitions or surge plates into Sections with less than 7,500L capacity.

2.2.3 Comparative Simulations

Comparative simulations were undertaken on several different configurations of DG transport, namely ISO tanks and DG road tankers with varying stability angles and deck heights. The simulations results showed that achieving the 0.4g SRT requirement currently in place for DG road tankers was typically impractical for ISO tanks (Figure 32). This difficulty arose due to the standardised dimensions of ISO tanks and limited fill level options causing a relatively high CoG compared to road tankers explicitly designed to reduce SRT by virtue of construction geometry as well as fill level options.

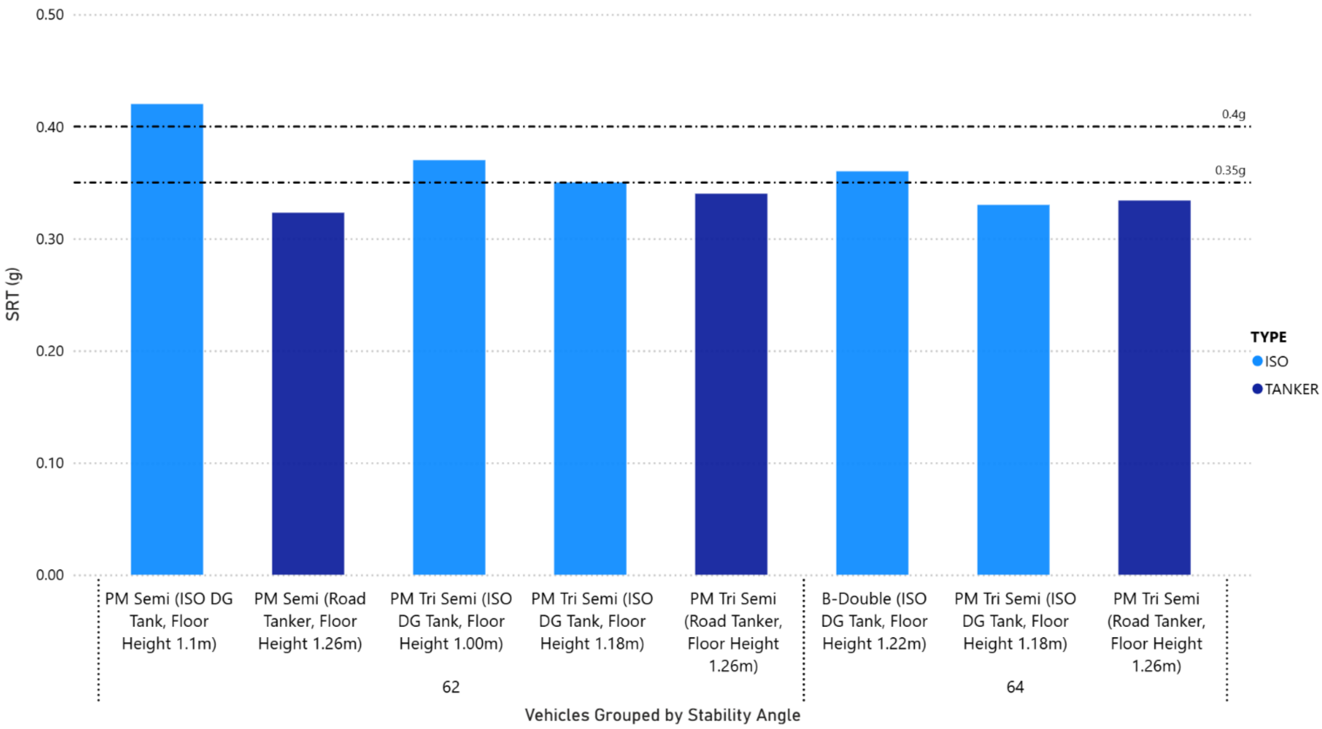

Figure 32 DG PM Semi SRT Results

Most ISO tank configurations did not meet the PBS requirement of 0.4g SRT. Even carefully designed ISO tank transport trailers with a deck height of 1.0m only meet an SRT of 0.37 rather than the 0.4g.

The introduction of a separate 0.37g performance level in the SRT standard for these vehicles would reduce ambiguity in the SRT standard, while maintaining a balance between safety and practicality for a vehicle type that has limited design flexibility.

2.2.4 Proposed Solution

The preliminary definition below is consistent with that of a *road tank vehicle* in the Australian Dangerous Goods (ADG) Code (2024) with additional clarification regarding portable and demountable tanks from AS 2809.1 (2023):

> ***Road tank vehicle*** *means a road vehicle of which a tank forms part or to which a tank, other than a portable tank, is attached. Vehicles that carry portable or demountable tanks which are filled or discharged while on the vehicle are deemed to be a road tank vehicle in these Rules.*

In line with this definition, the terminology used to apply the 0.4g performance level will be updated to use *road tank vehicle* rather than *road tanker*.

It is proposed that a new performance level of 0.37g be introduced and be applicable to vehicles carrying portable tanks containing dangerous goods. The NHVR believes raising the performance level from 0.35g to 0.37g strikes an appropriate balance between safety and practicality for vehicles carrying portable tanks containing dangerous goods.

The ADG Code contains fill level requirements for both road tank vehicles and vehicles carrying portable tanks when transporting liquids. While the PBS Rules state that assessments must be conducted using the least favourable load condition, consideration must also be given to relevant requirements of the ADG Code.

2.2.5 Technical Details of Recommendations

The following definitions will be added to Part 4 of the *PBS Scheme - the Standards and Vehicle Assessment Rules:*

***Road tank vehicle** means a road vehicle of which a tank forms part or to which a tank, other than a portable tank, is attached. Vehicles that carry portable or demountable tanks which are filled or discharged while on the vehicle are deemed to be a road tank vehicle in these Rules.*

Further, the proposed change to performance requirements is as follows:

Performance Based Standards Road Class	Performance Level Required
All Levels	Road tank vehicles hauling dangerous goods in bulk – not less than 0.4g. Vehicles carrying dangerous goods in bulk within a portable or demountable tank with a capacity of more than 7,500 litres – not less than 0.37g.

3 Rearward Amplification and High-Speed Transient Offtracking

3.1 RA/HSTO Proposed Approach Part I – Accommodate Stability Control Technology

3.1.1 Overview

As outlined in detail earlier, the RA and HSTO standards were first developed out of research and fleet studies from the 1990s and early 2000s, at a time when heavy vehicles were rarely equipped with stability control technology. Therefore, the lane change procedure and associated measures were set to manage rollover tendency and high-speed transient behaviour primarily through vehicle design, suspension characteristics and driver control, without any contribution from ESC/RSC. Since that time, both the technology and the fleet have undergone substantial change, while these standards have remained largely unchanged since the Scheme's inception.

While SRT is often the most prevalent gate-keeping standard barring entry, indeed, for certain combination types, RA and HSTO are the limiting standards restricting the vehicle's entry or resulting in limitations upon the maximum payload height to improve performance. For example, under the current assessment rules, some of these combinations exceed the RA or HSTO limits when tested at the required velocity of 88 km/h. However, physical testing has demonstrated that the same vehicles, when fitted with stability control technology, can improve their performance and successfully negotiate the required test manoeuvre, with ESC/RSC automatically activating the brakes to assist in rollover control.

As it stands, these requirements can also act as barriers for entry into the PBS Scheme for certain combination types such as Level 3 and Level 4 road trains. With the improved performance that stability control technology provides, these restrictions and barriers will be reduced, allowing more vehicles into the PBS Scheme and increasing productivity. As stated in Section 2.1.1, allowing more vehicles into the Scheme should also have a net safety benefit for Australia's heavy vehicle fleet.

It is important to note that technology advancements that improve vehicle performance have always occurred within the PBS Scheme. For example, steerable trailer axles have enabled longer combinations to pass the Low-Speed Swept Path standard. These steerable axles are programmed to lock above a certain speed so that they do not negatively impact vehicle performance at high speed. Thus, stability control systems will not be the first "smart" technology to aid in meeting the PBS standards. The inclusion of any new technology into the PBS framework is carefully considered, with a thorough analysis of the safety and risk profile associated with any proposed changes.

The NTC's *Reforming the PBS Scheme* has explicitly called for the incorporation of new technology and future innovations. The proposed RA/HSTO pathway is one way of giving effect to that direction in the high-speed standards. Since stability control technology has become widely adopted within the PBS fleet, and simulation methodologies and capabilities have significantly evolved since the Scheme's inception, it is timely to further enhance the standards to remain at the forefront of innovation and enable the consistent benchmarking of stability control systems in vehicle performance assessments.

3.1.2 Impact of Stability Control Technology on Performance

To quantify the influence of stability control on the assessment of RA and HSTO performance, a set of representative PBS vehicle combinations was modelled with and without RSC and assessed using the PBS lane-change manoeuvre in accordance with ISO 14791:2000(E). RA, HSTO and LTR were recorded from these for comparison between baseline 0.35g SRT vehicles without stability control and otherwise identical 0.32g SRT cases equipped with RSC. As with every test conducted throughout this paper using the module, no RCS/ESC was fitted to the prime mover.

Of the vehicles preliminarily modelled, five PBS compliant vehicles selected as representative and assessed through the lane change manoeuvre without RSC. Each vehicle was configured to an SRT of 0.35g. These vehicles were then modelled again with only their SRT performance altered to 0.32g through the increase of payload height. Essentially representing a PBS compliant vehicle that is carrying a higher load than usual and giving readily comparable performance. The A-Triple was the exception where it required a higher SRT to be able to meet the other PBS standards, and as such had an SRT of 0.44g. In the graph legends, 'PBS Compliant' refers to the version of the vehicles that have 0.35g SRT but were equipped with RSC, while 'RSC On' refers to the version of the vehicles that have an SRT of 0.32g with RSC activated.

It is crucial to recognise that the comparison is not quantifying the improvement of RSC to a 0.35g vehicle, but that of a 0.32g vehicle. As such the results are showing not only the change from the baseline 0.35g, but also the ability of the technology to raise (or lower) a poorer performing vehicle to achieve a similar performance outcome.

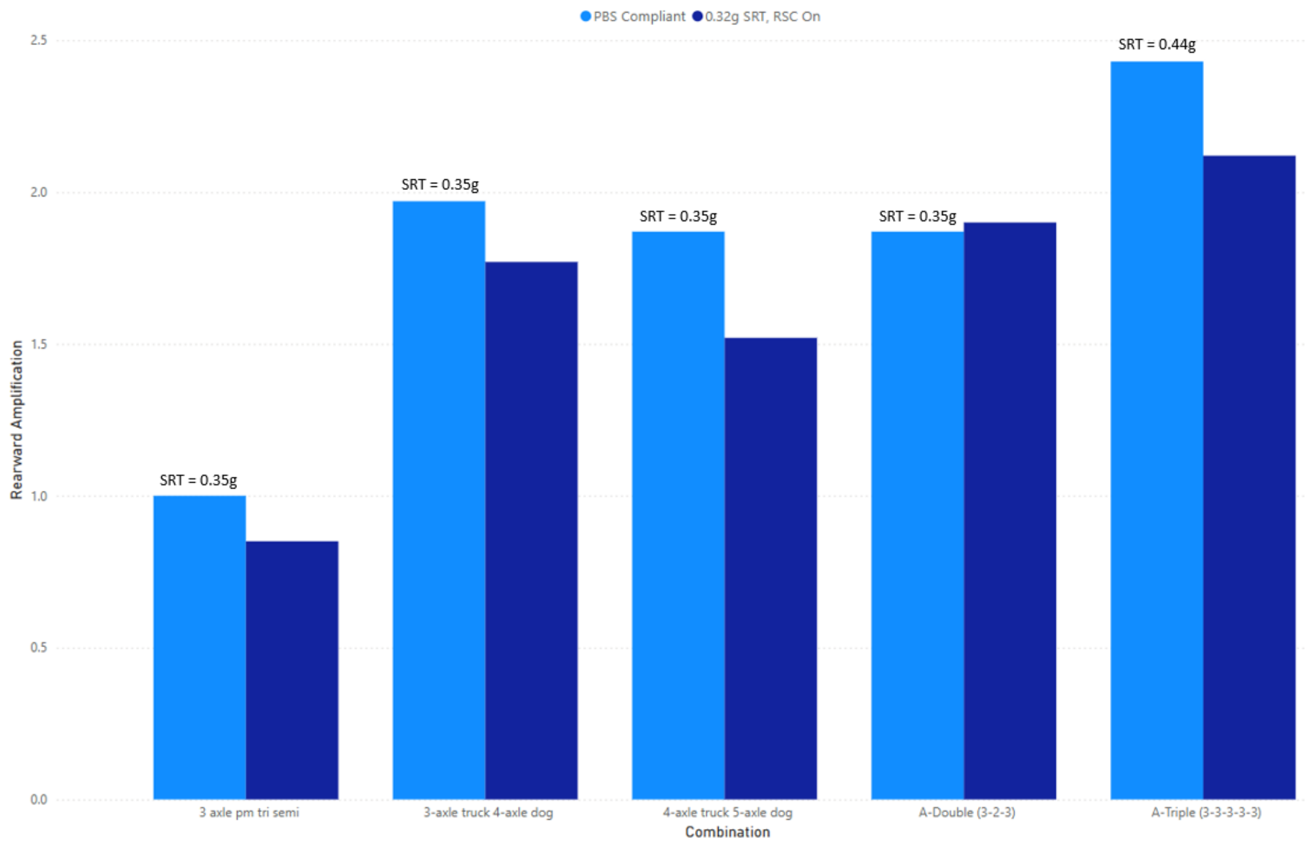

Figure 33 RA Performance on 88km/h Lane Change

When considering the resultant RA performance of the test vehicles, across the combinations, the 0.32g SRT vehicles equipped with ESC/RSC generally achieve equivalently or better to their respective 0.35g variants (Figure 33). The prime mover semitrailer, truck and dog, and A-triple all produced similar reductions in RA, with the 4-axle truck 5-axle dog and A-triple exhibiting the most pronounced improvements. The A-Double maintains a comparable RA performance in both configurations, diverging somewhat from the more pronounced outcome expected after the fashion of the field testing, which may be attributed to the proof-of-concept RSC module or its input, or the limits of the controller were reached regarding its ability to reduce the standard 0.32g RA A-Double to the level of the 0.35g non ESC/RSC benchmark case.

Regardless, the difference is negligible and a near match to the performance of a non-technology equipped vehicle, with the common outcome for the other combination types demonstrating a significant improvement.

The peak LTR values for the RSC equipped vehicles are similar to that of the results from the better-SRT, non-RSC baselines, with no discernible trend (Figure 34). All cases return an LTR less than 0.9. For most of these combinations, while the moderate change to SRT results in a more dynamically active response, the RSC can be seen to nuance or mute that almost entirely, such that there is approximately equivalent performance between the cases. That is, when simulated without RSC (not shown), the 0.32g combinations have worse LTR performance in this exercise. Hence there is a net benefit to the fitment of the RSC module by controlling instability to an equivalent performance of a PBS compliant vehicle.

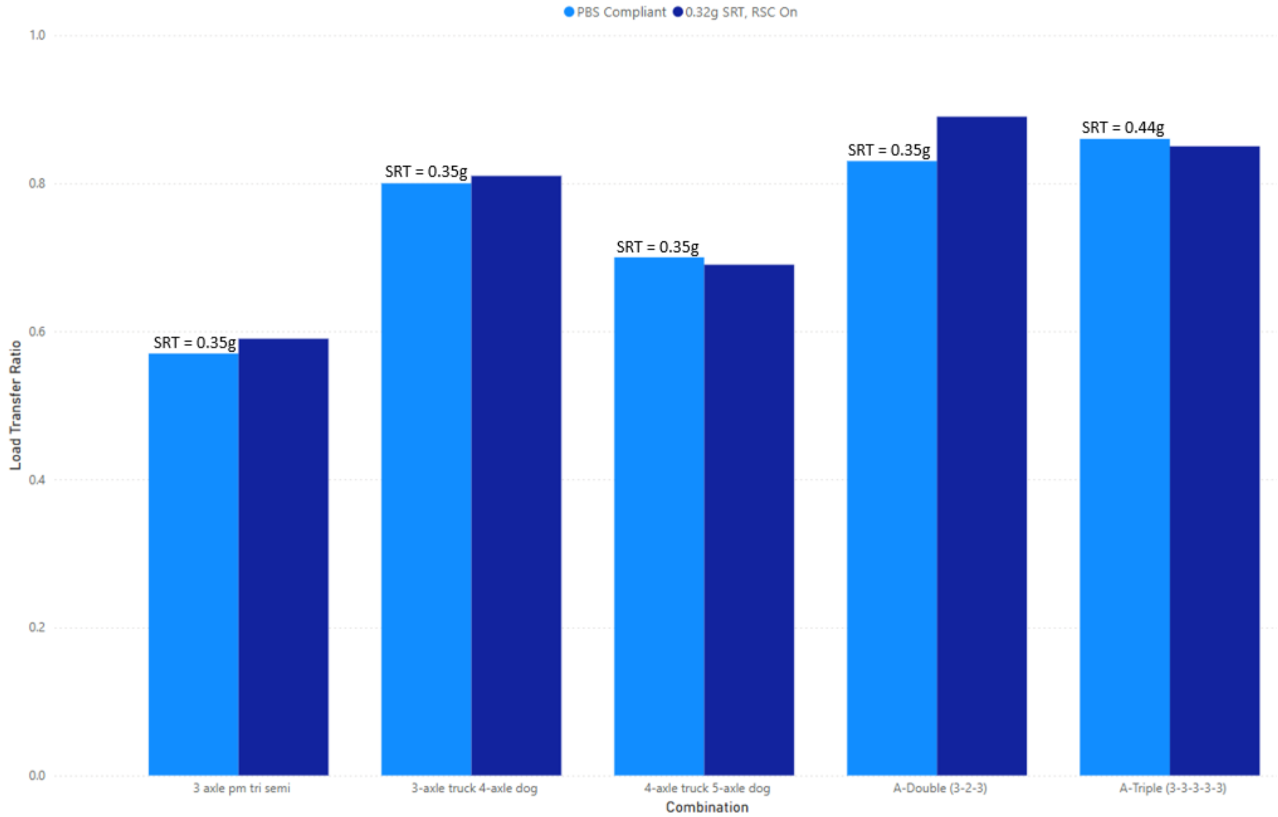

Figure 34 Load Transfer Ratio of Lane Change vehicles

The A-Double is again the outlier in this set of results, with the only perceptible discrepancy suggesting the limit of the RSC controller was reached in that instance. Further development with the incorporation of yaw instability may reveal additional insights.

Significantly, the LTR of those 0.32g SRT vehicles which would typically operate at borderline, or actual, rollover thresholds have seen dramatic reductions in their LTR such that they effectively meet the same performance as that of a vehicle with an improved inherent SRT achieved through the traditional pathway of physical, not technological, performance control.

A similar story is generated from the comparative of the vehicle's HSTO performances (Figure 35). Across the combinations, the 0.32g SRT cases with RSC remain in close contest with their 0.35g baseline counterparts. The lane change manoeuvre proved insufficient to trigger a significant control response from the prime mover semitrailer; likely due to its excellent performance in the test in either case, indicating that the lateral acceleration wasn't within the realm of the controller's thresholds for response.

The prime mover semitrailer complies with all PBS Level 1 requirements except for SRT (i.e. fails due to a 0.32g result). This configuration illustrates a case where fitting RSC technology can enable compliance with SRT requirements while allowing for increased load volume (i.e. payload height). A significant improvement was seen in the 3-axle truck 4-axle dog where the 0.32g case notable outperformed its non-RSC 0.35g baseline equivalent.

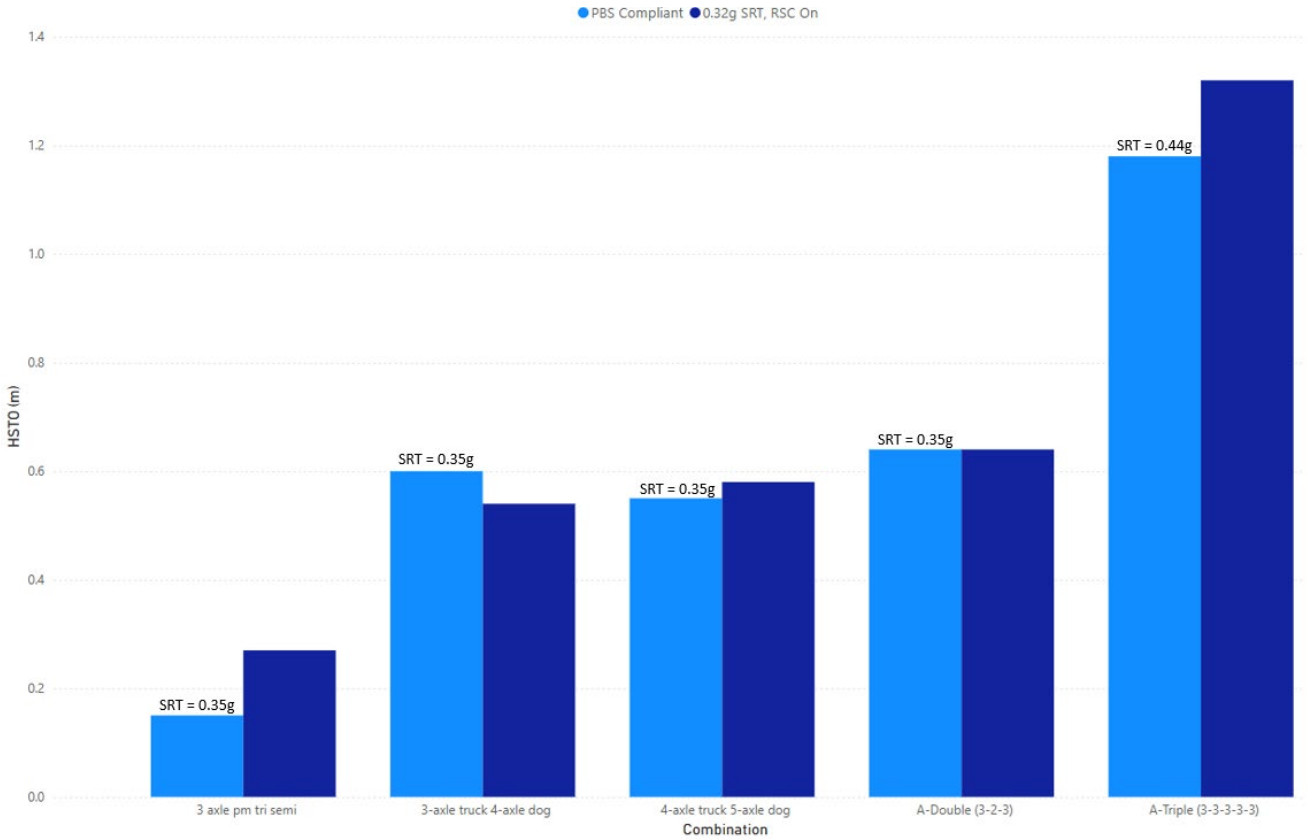

Figure 35 HSTO Performance on 88km/h Lane Change

An important observation is that where the greatest improvements in RA are observed (for example, the 4-axle truck 5-axle dog and A-Triple), the HSTO shows a near equal performance of those RSC vehicles to their baselines. That is, the HSTO cannot be said to have 'increased', since as noted earlier, the higher result is seen in the vehicle with the lower SRT, which would otherwise have a significantly greater HSTO result.

A previous study (Coleman 2010) in addition to the findings from the aforementioned physical testing of the A-double conducted in 2024 indicate that stability control technology should have a positive influence on HSTO performance. The results have demonstrated that the RSC controller in lower-SRT vehicles resulted in improvements in multi-combination vehicles such that their HSTO result was approximately equivalent to that of traditional 0.35g baseline respective vehicles.

3.1.3 Double Lane Change Example

A preliminary assessment of the double lane change manoeuvre, for indicative purposes only, was conducted on two identical vehicles to further illustrate the safety benefit RSC produces within a more severe manoeuvre. Further investigation would be required to determine its suitability and specific design appropriate to the Australian heavy vehicle fleet. Similar to the above, two identical A-doubles were simulated with the only difference being that of SRT and RSC fitment.

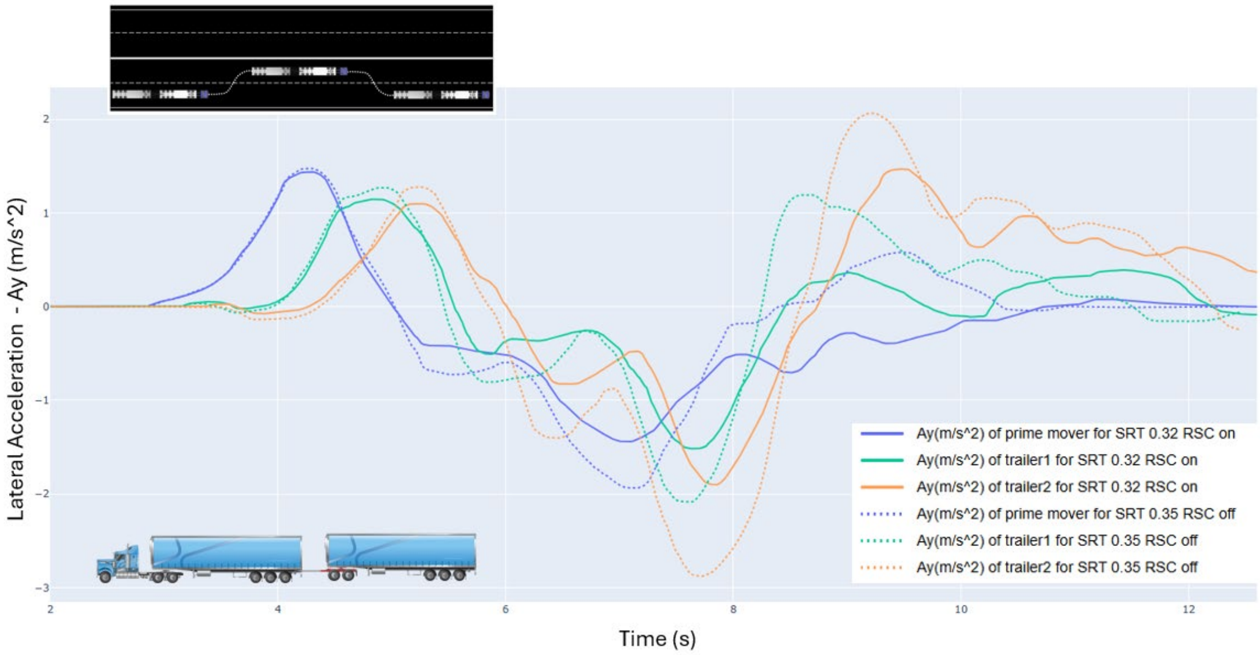

Figure 36 Double Lane Change test of A-Double showing effectiveness of RSC in lateral accelerations

The lateral acceleration traces recorded in Figure 36 indicates that the RSC technology effectively controlled the peak response as compared to the 0.35g vehicle without RSC with a significant reduction in the felt lateral acceleration. Importantly the total change in lateral acceleration on the rearmost trailer critically controlled by the RSC with a pronounced reduction that can be seen in the lead trailer upon the vehicle's return to lane.

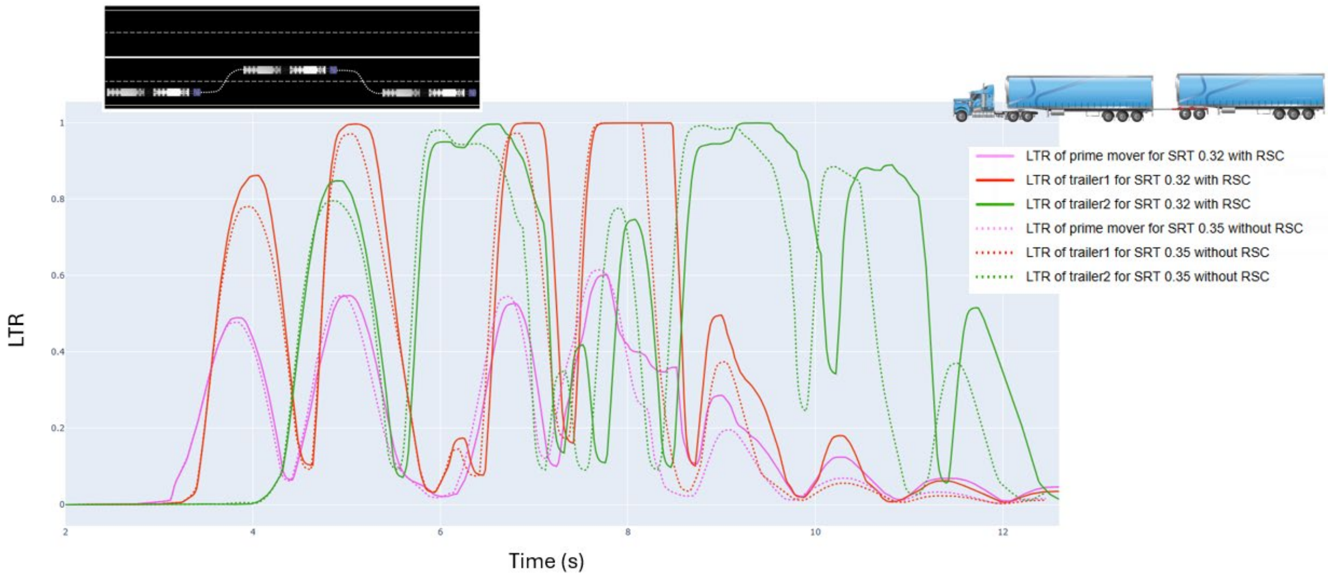

Figure 37 Double Lane Change test of A-Double showing effectiveness of RSC in LTR

The LTR records a more significant response to the load shift on the trailers of the 0.32g SRT vehicle with RSC, with similar peaks upon the rear trailer (Figure 37). Despite the lower SRT, corresponding to a payload height difference of approximately 300mm, and a reduced static stability threshold, thereby being particularly prone to excitation in a severe manoeuvre, the RSC demonstrated its benefits via the outperforming of the baseline 0.35g vehicle. The RSC equipped trailer can be seen to sufficiently dampen the LTR instability and rapidly affect the duration of the vehicle's LTR at the extreme threshold point (i.e. LTR 1.0). An appropriate double lane change manoeuvre will continue to be investigated but is not proposed within this single option.

3.1.4 Lane Change Braking

When the vehicle brakes because of RSC activation, unavoidably there is typically greater than 3km/h of speed lost during the manoeuvre which, under the current PBS rules, would be deemed an unsuccessful test. The current lane change requirement of no more than 3km/h deviation from the prescribed test speed was instituted to represent an emergency avoidance manoeuvre at highway speeds without braking. This requirement of the lane change test in some cases may be a direct barrier to the adoption of RSC technology and will need revising for RSC technology to be effectively integrated into the PBS assessment rules.

That is, the original intent remains the same, as braking caused by ESC/RSC is automatic and not activated by the driver of the vehicle. Given the analysis above, what is proposed constitutes an alternative RA and HSTO assessment process for vehicles with an SRT not less than 0.35g fitted with stability control technology where the manoeuvre remains the same, as does the minimum lateral acceleration to be generated on the steer axle and the steer frequency and other specifics remain the same. Such that the vehicle can demonstrate its stability performance, including an additional LTR limitation, such that it ensures it will affect no material change to the risk profile.

3.1.5 Proposal

The intent of PBS standards is to assess the on-road performance of heavy vehicles. The RA and HSTO test procedure was selected to be representative of a real-life avoidance manoeuvre. Not allowing vehicles with stability control technology to reduce their speed in this manoeuvre would be going against the purpose of the standards as the vehicle would no longer be performing as it would in real-life. By updating the speed requirements, the test procedure will be fit-for-purpose for the vehicles now on Australia’s roads.

As stability control technology has the potential to improve vehicle performance in dynamic, high-speed manoeuvres which the RA and HSTO standards are designed to address, it is proposed that this technology could be included as an alternative path to demonstrate compliance during PBS assessments.

An LTR of 0.9 has been selected as the limit for the LTR requirement when conducting the alternative tests, which only applies to vehicles accessing the alternative technological pathway to achieve compliance (see Section 4). Vehicles which do not have RSC fitted to all units must still comply with the standard requirements of PBS assessment rules. The performance requirement for the high-speed dynamic standards of RA and HSTO are still the same, with the RA result being assessed against an SRT equivalent of 0.35g despite the vehicle having a minimum permissible SRT of 0.32g.

Any requirements currently present in the Rules that would prevent the technology from being used in assessments will also be updated accordingly for this alternative approval process. This includes removal of the test procedure requirement to maintain a constant speed of 88 km/h (with tolerances specified in ISO 14791:2000(E) (2000)). Since stability control technology will often cause a speed reduction to stabilise the vehicle, this requirement will be modified. Instead of a constant speed requirement, vehicles fitted with stability control technology will have an entry speed requirement with automatically commanded braking from the stability control system being permitted during the manoeuvre.

The RA and HSTO standards would be revised to provide an alternate test specification that is only applicable to vehicle combinations in which all units are fitted with a vehicle stability function that includes roll-over control. This alternate test specification would only differ by its speed requirements and tolerances, to be investigated for the implementation of the proposed change.

Alternative Test Specification

This alternative test specification will only be applicable to vehicles eligible for alternative SRT performance level (Section 2.1) and does not apply to combinations requiring a higher SRT under the PBS Assessment Rules.

For any vehicles using the alternate specification, the Performance Levels for both RA and HSTO would be expanded to introduce an additional measure of LTR (see Section 1.3.5 for further details).

The NHVR’s preliminary position is that the calculation of the RA performance level would be modified to set a floor of 0.35g for vehicle combinations in which all units are fitted with a vehicle stability function that includes roll-over control. This is only necessary if SRT proposed approach - Part I is implemented as it would allow vehicles to have an SRT below 0.35g in the Scheme.

Table 1 Rearward Amplification (RA) - performance based standard values

Performance Based Standards Road Class	Performance Level Required
All Levels (for vehicles with no less than 0.32g SRT fitted with stability control technology)	Rearward amplification not greater than 5.7 times the representative static rollover threshold deemed to be a value of 0.35g; and LTR not greater than 0.9

Table 2 High-Speed Transient Offtracking (HSTO) performance based standard values

Performance Based Standards Road Class		Performance Level Required
For vehicles with no less than 0.32g SRT fitted with stability control technology	Level 1	HSTO no greater than 0.6 m and LTR not greater than 0.9
	Level 2	HSTO no greater than 0.8 m and LTR not greater than 0.9
	Level 3	HSTO no greater than 1.0 m and LTR not greater than 0.9
	Level 4	HSTO no greater than 1.2 m and LTR not greater than 0.9

3.2 RA/HSTO Proposed Approach Part II – Test Speed for Vehicles Unable to Achieve 88 km/h

3.2.1 Overview

PBS Assessors are required to assess a subject vehicle as per the *Performance Based Standards Scheme – the Standards and Vehicle Assessment Rules*. Vehicles that are unable to achieve a speed of 88 km/h are deemed to fail the RA and HSTO standards as they cannot comply with the requirements of the standards' test procedure. It is proposed that the standards are updated to allow an alternative approach for compliance via comparison with an approved PBS vehicle at an alternative test speed. The alternative approach would only be applicable for subject vehicles that do not have the capability to achieve 88 km/h. Vehicles that are speed limited specifically to enable use of this alternative approach will not be accepted.

Allowing the lane change test procedure at an alternative speed is in-line with ISO 14791:2000(E) (2000), which states that the test should be conducted at the maximum speed of the vehicle if it is less than 80 km/h (the lowest test speed stated in the standard). The required lateral acceleration and steer frequency requirements (0.15g and 0.4Hz respectively) will be maintained, and the test course modified with respect to test speed.

It is important to note that the test procedure within the RA and HSTO standards does not represent a "worst-case" avoidance manoeuvre, rather it is used as a tool to compare vehicle performance against a benchmark that is considered acceptable. Since this proposal involves comparison against PBS vehicles already approved on the road, this proposal remains consistent with the original intent of the standards.

Any issues arising from vehicles not being able to operate at posted speed limits are considered outside the scope of the PBS Scheme. Determining whether a vehicle is travelling abnormally slowly depends heavily on the driving environment and is generally governed by state-specific road rules. The PBS Scheme does not have the ability to exempt vehicles from these road rules. This proposal represents an alternative means of assessment for these vehicles by which performance requirements are translated from the existing Rules for a lower speed environment.

3.2.2 Impact of Test Speed on RA, HSTO and LTR Performance

Simulations were conducted for several different combinations at speeds of 50, 60, 70 and 88km/h to assess the impact test speed had on the performance of RA, HSTO and LTR. The combinations included in these simulations are a 3-axle Truck and 4-axle Dog (Truck and Dog), 3-axle Prime Mover Tri-Semitrailer (PM-Semi), A-Double and A-Triple, representing a range of vehicles in the fleet that have varying high-speed stability performance. The speed test simulations were conducted on the standard ISO 14791:2000 single lane change shown in Figure 38. One of the key features of the manoeuvre is the lateral acceleration of 0.15g on the steer axle, to induce this input to obtain valid results when performing the test at a lower speed, a tighter steer path must be followed. The adjusted steer paths for each input speed is shown in Figure 39.

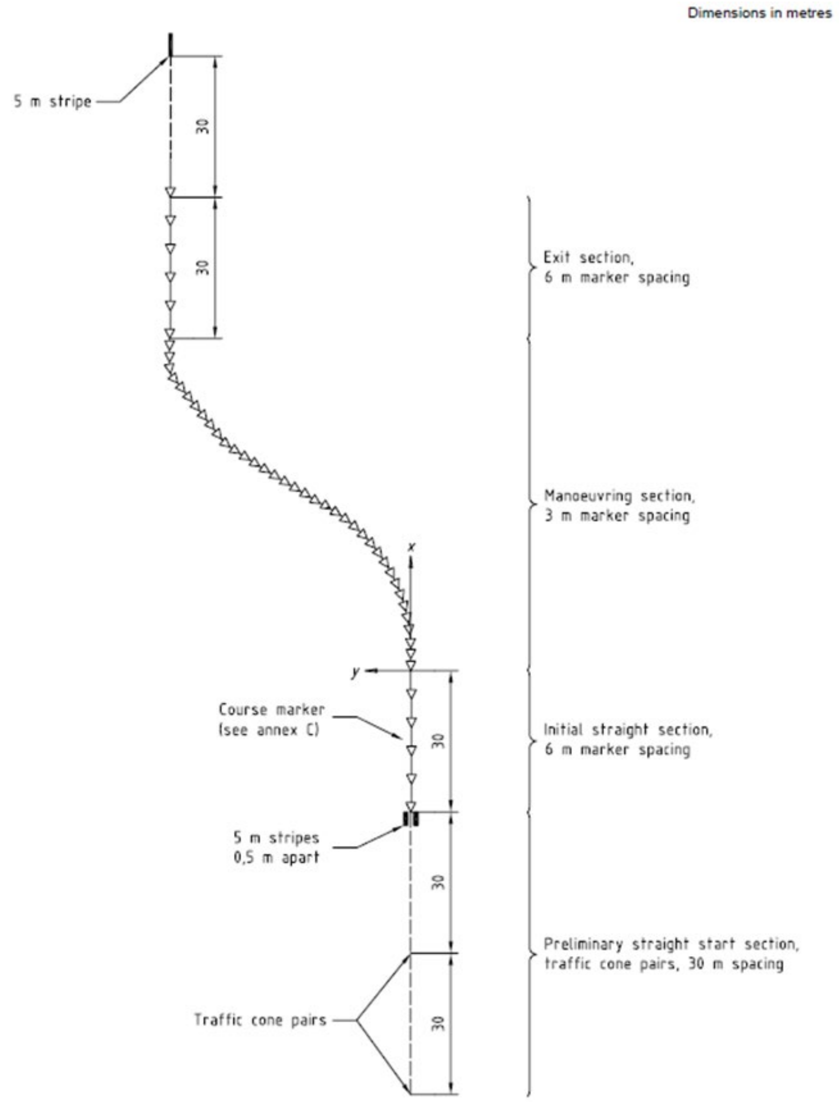

Figure 38 ISO 14791:2000 Single Lane Change Test Course (ISO 2000)

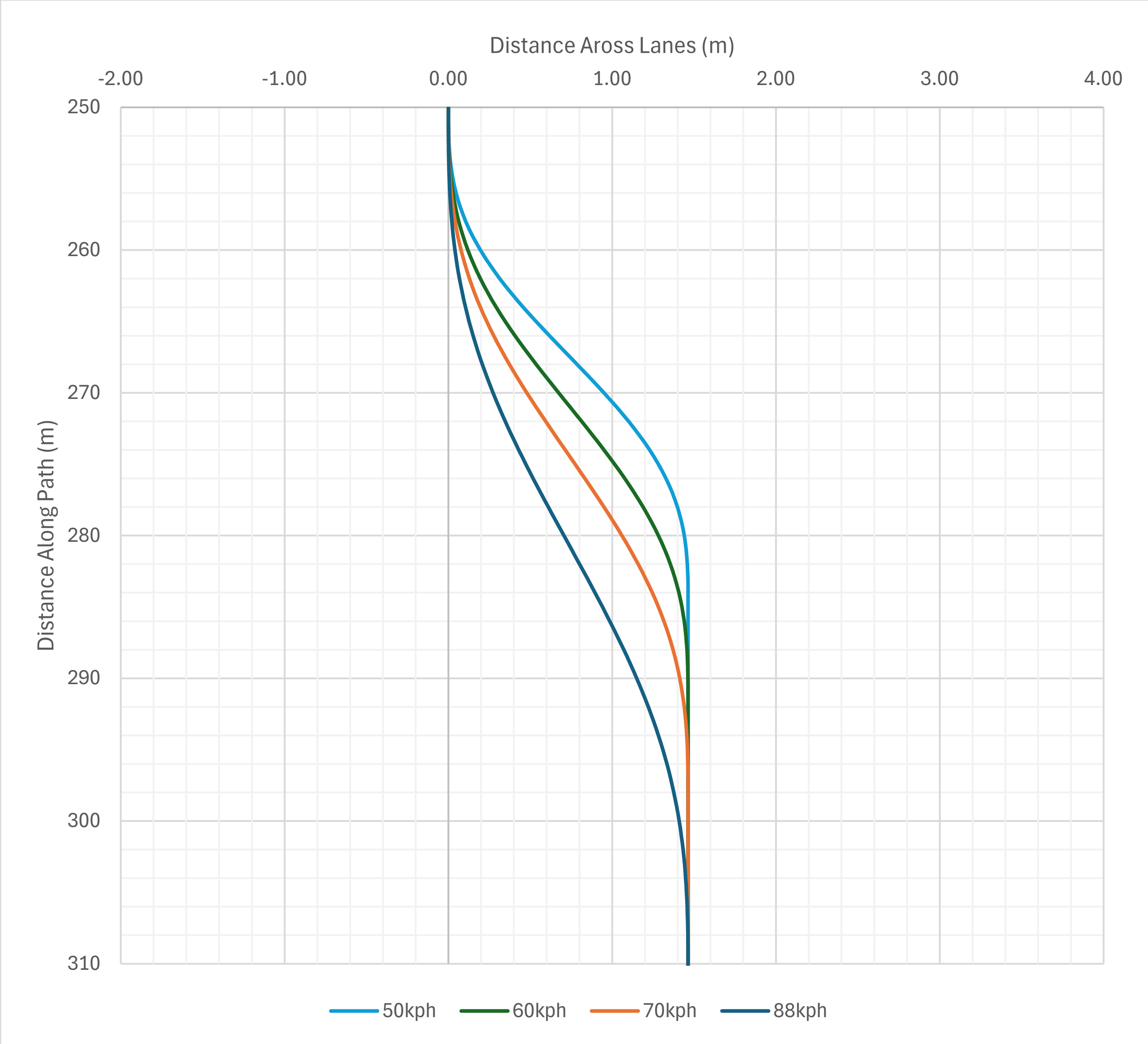

Figure 39 Lane change path at 0.15g

The graph in Figure 40 shows the RA values for each test speed and combination. While no configuration demonstrates a "perfect" linear relationship, there is a general upward trend of the data, suggesting that RA increases relative to increases in test speed. The Truck and Dog has a consistently higher RA than the A-Double, which in turn has a consistently higher RA than the PM-Semi. The most outstanding result is of the A-Triple, which at 50km/h has the lowest RA, yet at 88km/h has the highest RA. The A-Triple is the only combination that has three trailer units, all other combinations have two, demonstrating the significant impact number of units in a combination has on the high-speed and low-speed stability of a unit. At lower speeds, longer combinations show better performance in RA, but at higher speeds these combinations perform worse. Ultimately, the vast differences in RA values across configurations suggests that for a vehicle to pass RA at a lower test speed, it needs to be compared to the performance of a similar configuration that already passes the PBS at the 88km/h test speed.

The relationship between LTR, RA and HSTO and the test speed is non-linear and configuration dependent which adds difficulty to setting specific performance criteria at different speeds. Instead, the use of like-for-like comparison demonstrates that the subject vehicle does not pose any additional risk than an otherwise approved PBS vehicle by ensuring the subject vehicle's performance is no worse than that of an approved PBS vehicle at the same test speed. This is in line with the already established PBS exemption process under Section 9, "The Regulator may consider that while a heavy vehicle built to a design does not comply with a standard under the Standards and Vehicle Assessment Rules, it will not pose any greater risk than a heavy vehicle that complies with the standard".

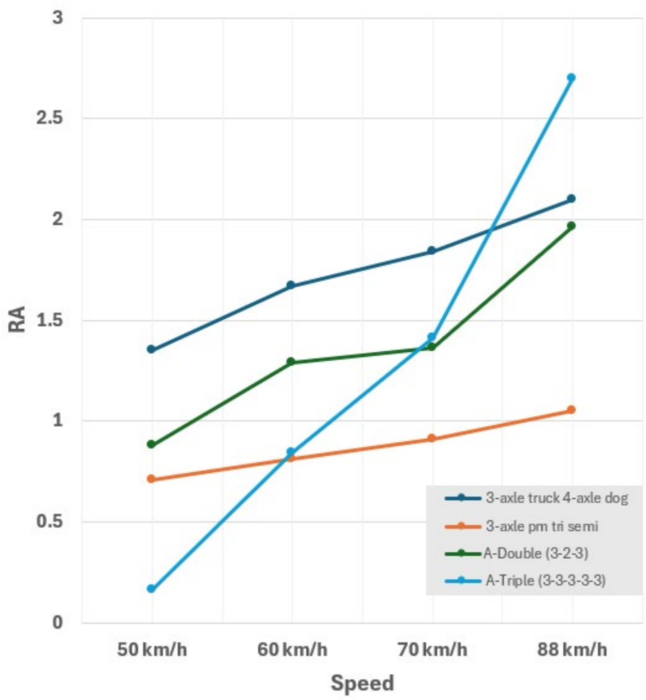

Figure 40 Impact of test speed on RA

Figure 40 shows that RA is reduced as speed decreases in a non-linear fashion and the spread of results converges at the lower speeds. This non-linear and configuration-dependent sensitivity of RA to speed reveals that a reduced test speed is not a simple scaled application of the standard 88 km/h result. Hence reinforcing the need for like-for-like comparison against an approved reference vehicle rather than utilising an 'adjusted' RA limit.

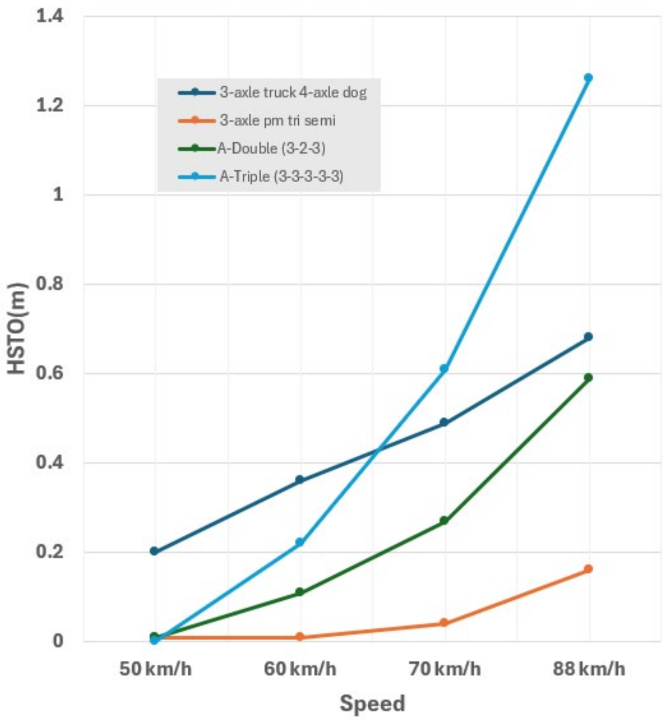

Figure 41 Impact of test speed on HSTO

The increasingly steep rise in HSTO as a function of higher speed, particularly in the A-coupled vehicles demonstrate that comparatively small changes in velocity can generate disproportionate gains in offtracking. As speed decreases, HSTO reduces non-uniformly between the combination types, converging at the lower speed (Figure 41). A speed specific criteria would produce an unreliable performance indicator compared to an appropriate comparison reference vehicle.

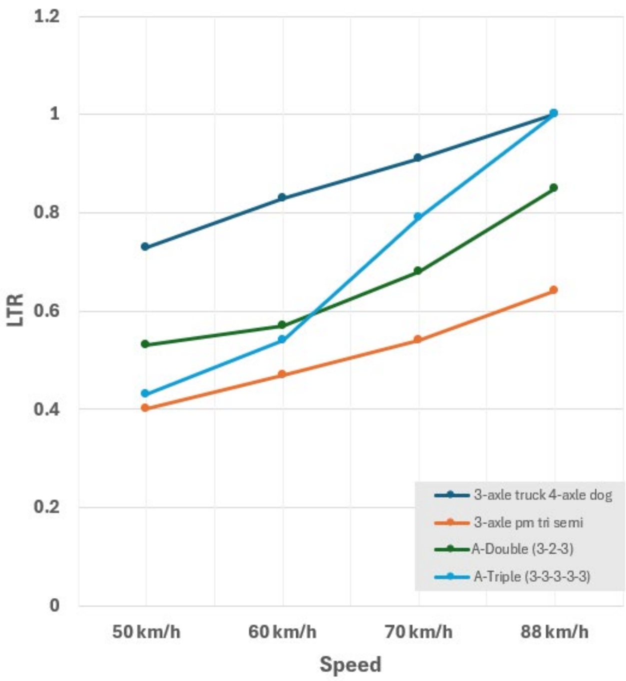

Figure 42 Impact of test speed on LTR

LTR exhibits varying rates of change across vehicle configurations, where notably, the A-Triple rapidly approaches the boundary condition in response to incremental speed increases (Figure 42). While the Truck and Dog begins at a considerably higher LTR position, it trends more incrementally with respect to speed increases. Rollover tendency as expressed by LTR, similarly then, responds in a configuration dependent, rather than linear, response.

The data correlates with the understanding that vehicles with non-roll-coupled units exhibit greater differences in performance as test speed increases when compared to roll-coupled combinations. With the A-Triple specifically, differences in performance are larger as speed increases due to the higher number of articulation points across the combination. These findings align closely with those in the NRTC fleet study (Prem et al. 2002) (see Section 1.3.3 for further details) and demonstrate the variability across different configurations and speeds, meaning a comparative reference vehicle, rather than a scaled or adjusted speed, would be more appropriate.

3.2.3 Technical Details of Proposal

The RA and HSTO standards would be expanded to include an alternative test specification for subject vehicles that do not have the capability to achieve 88 km/h. The existing test specification and performance levels will remain for all other vehicles. Vehicles that are speed limited specifically to enable use of the alternative test specification will not be accepted.

Alternative test specification

An existing, approved PBS vehicle design of the same access level and configuration as the subject vehicle is to be identified by the assessor. The comparison vehicle combination is to be of the same characteristics such as number and type of articulation points, relative masses and lengths etc. If no such vehicle can be identified, existing and approved PBS vehicle design with the same access level and configuration as close to the subject vehicle as possible must be used. This vehicle will be referred to as the *reference vehicle* for the rest of this document.

Both the subject vehicle and reference vehicle must execute a single lane change manoeuvre in accordance with the "Single Lane-Change", "Single Sine-Wave Lateral Acceleration Input", specified in ISO 14791:2000(E) (2000). This is recommended to be modified according to the speed which generates the same lateral acceleration response at the same frequency as the standard path, only at the reduced speed (Figure 39). The manoeuvre must have a maximum lateral acceleration of not less than 0.15g and a steer frequency equal to 0.4Hz. The test must be conducted at the maximum physical speed of the subject vehicle.

Allowed error from the specified path is to be unchanged from the existing test specification.

Performance levels for the alternative procedure are as follows:

Table 3 Alternative performance levels

Performance Based Standards Road Class	Performance Level Required	
	RA	HSTO
All Levels	$\frac{\mathrm{RA}_{subject\ vehicle}}{SRT_{subject\ vehicle}} \leq \frac{RA_{reference\ vehicle}}{SRT_{reference\ vehicle}}; and$ $LTR_{subject\ vehicle} \leq LTR_{reference\ vehicle}$	$HSTO_{subject\ vehicle} \leq HSTO_{reference\ vehicle}$ $LTR_{subject\ vehicle} \leq LTR_{reference\ vehicle}$

3.2.4 Other considerations

When speed is reduced below a certain level, the Single Lane-Change manoeuvre can no longer be reliably used to evaluate RA and HSTO performance. Therefore, a minimum speed will be specified for the alternative test specification. Further investigation into an appropriate minimum speed will be conducted by the NHVR as part of the implementation of this proposal.

4 Load Transfer Ratio (LTR)

4.1.1 Overview

Since LTR is a direct measure of the transfer of load from one-side of the vehicle to the other, it can provide additional insight into vehicle stability that is not provided by the RA and HSTO measures. It is also easily measured in the simulation environments used by PBS Assessors in Australia. Rather than introduce Load Transfer Ratio as a separate standard in the *PBS Scheme – the Standards and Vehicle Assessment Rules* as done in other schemes around the world as outlined in Section 1.3., LTR is being used as a supplementary measure to provide an additional level of assurance for many of the changes proposed.

Currently, it is possible to have a combination that can achieve the RA and HSTO requirement in a lane change, but do so with an LTR of 1.0, which means the vehicle could be close to a dynamically instable situation, and is not addressed within the current standards.

With the inclusion of LTR into these dynamic tests these risks are addressed, and the dynamic behaviour and response of the combination under active conditions can be ascertained.

Although it won't appear as a separate standard in the *PBS Scheme – the Standards and Vehicle Assessment Rules*, the following calculation will be added to detail how LTR is to be determined in assessments (Ervin and Guy 1986):

$$LTR_{rcu} = \frac{|\sum(F_{L-} F_R)|}{\sum(F_{L+} F_R)}$$

Where:
rcu refers to roll-coupled unit

F_L refers to total normal force exerted by the tyre(s) on the left side of the axle

F_R refers to total normal force exerted by the tyre(s) on the right side of the axle

$\sum$ indicates summation over all the roll-coupled unit's axles except the steer axle(s) of the hauling unit

For units containing multiple roll-coupled units, the largest LTR value is presented.

4.1.2 Application within standards

LTR will be used as a supplementary measure in SRT proposed approach part I and RA/HSTO proposed approach part I and part II. Preliminary performance levels for LTR have been included in these proposals but these will be reviewed as part of the implementation process to ensure they are appropriate.

As the measurement of LTR does not require any additional test procedure, the resource impact on assessments should be minimal.

It is important to note as mentioned previously, that even though LTR is to be calculated for each roll-coupled unit, there are instances in the analysis for the proposed approaches where LTR is presented for each individual unit. This is done purely to provide additional insights into the vehicle behaviour being analysed but is unnecessary to measure performance in this metric.

The LTR limit of 0.9 was selected as it provides assurance that vehicles are not trending towards the boundary of dynamic stability, while being achievable by a vast majority of vehicle combinations in Australia's heavy vehicle fleet. 90% of the vehicles tested in NRTC's fleet study (2002) achieved this limit, and the NHVR deemed this as a sufficient preliminary limit for its purpose as a supplementary measure.

5 Implications for Australia's Heavy Vehicle Fleet

5.1 Alternative Pathways for Entry

The proposals for the inclusion of technology in the PBS Rules introduce an alternative assessment pathway previously not considered or evaluated. Importantly, they do not reduce the safety expectations of the PBS Scheme but rather impose further controls on cases seeking to enter the Scheme through this new pathway which considers the impact and influence of technology upon a heavy vehicle's dynamic performance. Where these vehicles must demonstrate performance results that is at least equivalent to that required under the existing standards for vehicles. In all cases, the proposed options retain or strengthen the safety envelope as indicated by the above analysis. Particularly with respect to the findings that a vehicle of 0.32g SRT when operating with the RSC module outperformed that of a 0.37g SRT vehicle in both transient and dynamic-operational simulations.

The proposed introduction of an LTR ≤ 0.9 performance requirement, when RSC is used, into the RA and HSTO standards directly addresses this finding. In practice, this means that access to the alternative SRT band (0.32g ≤ SRT < 0.35g) is conditional not only on the fitment of stability control technology, but also on the demonstrated capability of the vehicle to control load transfer and meet performance outcomes. Thus, maintaining continuity with the PBS methodology of a performance under representative benchmarking, whilst developing the Scheme forwards to recognise and incorporate the benefits provided by modern control technologies.

The alternative pathway which accommodates vehicles that do not (or are unable to) operate at the speeds required for high-speed manoeuvres is not without historical precedent. In the past, for example, the PBS Scheme has accommodated technological innovations, with conditions, for an innovative electronic steerable converter dolly. Operating conditions were imposed regarding the vehicle's in-service performance, checks and monitoring. A vehicle speed limitation was also prescribed, and accepted by the PBS Review Panel, whereby the vehicle's speed must not exceed 60km/h. This precedent illustrates that where technology-based departures from the norm, including departures from standard test speeds, are permitted, they are balanced by clear constraints, demonstrating that the Scheme can safely accommodate alternative speed assessment and operation when they are coupled with explicit performance and assurance that the risk profile is not adversely shifted.

Further, it must be emphasised that the provision of this alternate technology-based and alternative-speed pathways of assessment still comprehensively require that the vehicle meet the all the performance requirements and is not exempt from those other requirements not addressed in the Phase 4 proposed changes. The alternative entryway proposed does not remove the existing standards for PBS vehicles and a vehicle may continue to be assessed and enter the Scheme via the existing non-technology and/or high-speed pathways.

5.2 Future Fleet and Expected Safety Benefits

Notably, the only option for substantive change to the baseline is the proposal clarifications to the SRT requirement for dangerous goods vehicles, removing existing ambiguity and requiring an explicit higher safety margin by raising the SRT for certain vehicle types as outlined in the Sections above. Increasing the performance requirement there may have the potential to impact the accessibility of the PBS Scheme for some vehicles, including existing PBS vehicles. The NHVR will evaluate these impacts and explore appropriate measures to address them as part of implementing this proposal.

More obviously, the recognition within PBS of RSC/ESC as tied to performance outcomes is expected to influence the composition of the fleet over time; with new vehicles entering the Scheme via the alternative pathway made available by technology, but also retrospectively existing vehicles which may be unable to meet current requirements due to physical restrictions of payload and thus an inability to meet 0.35g SRT. Since SRT is inextricably linked to payload height, a reduction in SRT, in simplistic terms, is typically associated with an increase in payload height.

That is, the new options for assessment are expected to enable entry to the PBS Scheme for some combinations that are currently excluded because their freight task or design characteristics prevent their reduction of the centre of gravity height to meet 0.35 g SRT. These may be vehicles which, due to certain characteristics, 'gross out' before they 'mass out'. Examples of these vehicles include combinations with 0.32g SRT that may even pass all other PBS requirements or combinations that are unable to pass SRT due to the physical characteristics of their payload. RSC technology in these cases would benefit the dynamic stability of the vehicle. Under the proposed changes, these vehicles may instead demonstrate their performance characteristics and behaviour when equipped with stability control technology and assessed per the dynamic requirements proposed.

For existing PBS vehicles, the proposals also generate a productivity opportunity via this pathway for retrofitting stability control technology to gain access to higher payload heights where they currently are restricted in order to achieve the 0.35g SRT requirement. Where their performance can be assessed against the proposed alternate method, a relatively small shift in static SRT arising from increased payload height would be expected to deliver substantial improvements in productivity and freight task efficiency. Noting that these vehicles would be required to show that their dynamic performance, as discussed above, remains at least equivalent to that of current 0.35g designs without stability control. As shown in preceding Sections, the proposed minimum SRT for this pathway would not be less than 0.32g, a reduction not even reaching 10 per cent, yet the dynamic performance achieved by the assistive benefit of stability control technology can be expected to match, if not notably regain the risk profile by a greater margin than 10%. Such that the overall risk profile is not adversely affected. Further, while modelling on the impact to the overall freight task is a subject for a future investigation, it would be expected that the increase in allowable payload height would reduce the freight task trips, thereby resulting in benefits which spill over into economic, environmental and other time-on-the-road related metrics.

The NHVR estimates that there are over 4,000 trailers without stability control technology currently operating in the PBS Scheme. While upcoming changes to the DSUB standard as noted earlier will require that new trailers entering the Scheme are fitted with RSC, this does not provide an incentive for existing trailers to be retrofitted. By explicitly recognising these modern safety technologies as a means of receiving productivity gains, the Phase 4 proposals provide such an incentive. This would result in retro-fitment of ESC/RSC to suitable existing vehicles, combined with reassessment under the alternative pathways, which is expected to have a positive safety impact while also enabling productivity improvements where the dynamic requirements can be met. Thereby further raising the safety profile of the PBS fleet for both new, and importantly, existing vehicles which would otherwise continue to operate without the benefit of modern stability technology.

Finally, implementing these changes to the standards that add capacity for technology to be included in the assessment of vehicles may be the catalyst that encourages the development of other tests and technologies into the Australian PBS fleet. In doing so, PBS continues its long-standing role as a vehicle for innovation, safety and productivity.

6 Conclusion

The NTC policy paper 'Reforming the PBS Scheme' (2018), which was the key driver behind this review of the PBS standards, specifically recommended that it consider "the effects of new technology, and catering to future technology". The approaches proposed strongly align with this recommendation.

These PBS standards have not been updated for close to two decades, during which time numerical modelling capability and the technology used in Australia's heavy vehicle fleet have advanced significantly. These changes would advance the Scheme, better allowing the use of technology to comply with the standards.

The proposals developed through this review address four key areas. They close gaps in clarity, broaden the treatment of test speed in assessment manoeuvres and further develop the Rules to incorporate modern technological advancements. These proposals introduce an alternative SRT pathway whereby combinations in the range 0.32g ≤ SRT < 0.35g may be approved if they are fitted with stability control and, critically, demonstrate satisfactory dynamic performance. The inclusion of LTR ≤ 0.9 on specific manoeuvres for these vehicles provides a direct constraint on threshold behaviour, addressing a deficiency in the current framework where vehicles may satisfy RA and HSTO requirements while still exhibiting substantial near-boundary rollover load transfer. Furthermore, it provides greater insight into the vehicle's dynamic response and stability throughout the test, not otherwise reflected in RA, HSTO, or SRT.

Proposed updates to RA and HSTO introduce an additional assessment pathway that allows alternative-speed, comparison-vehicle assessments, and recognise the role of ESC/RSC, again with an LTR control to prevent operation at or near rollover. Finally, where previously there was the potential for inconsistent application of the standards, the proposed changes clarify and refine the SRT requirements for dangerous goods vehicles, removing the reported ambiguity and providing an increased safety requirement.

In conclusion, the proposals operate in two distinct ways. The proposed clarification to dangerous goods SRT represents a refinement of the baseline requirements, whereas the alternative speed assessment and technology-based assessment approaches set out in this paper are adjunct pathways to the existing standards. These approaches provide an alternative method of assessment that an applicant may elect to use for benchmarking and evaluation for entry to the Scheme. The original standards remain, and the proposed pathways operate as an alternative means of access with additional procedures and considerations given to alternative-speed and/or technology-based entry.

These changes open the door for further improvements in the safety and productivity of Australia's heavy vehicle fleet and allow for continued innovation in vehicle design, which is a cornerstone of the PBS Scheme.

7 References

ACEA (European Automobile Manufacturers Association) (2012) *Performance-based standards and indicators for sustainable commercial vehicle transport*, ACEA.

Anderskey F and Conklin R (2008) *Road map for the future making the case for full-stability*, Bendix Commercial Vehicle Systems LLC

AS (Standards Australia) (2023) *AS 2809.1:2023 Road tank vehicles for dangerous goods Part 1: General requirements for all road tank vehicles*, Standards Australia.

ATA (Australian Trucking Association) (2022) *Rigid drawbar converter dollies specification guidelines*, ATA.

Battelle (1996) 'U.S. department of transportation comprehensive truck size and weight study report no. 4', *1995 Truck Size & Weight Performance-Based Workshop*.

Chandrasekharan S (2007) *Development of a tractor-semitrailer roll stability control model*, The Ohio State University.

Coleman MP (2010) *Performance based standards and active vehicle stability systems*, National Transport Commission Australia.

Coleman M, Kovalev R, Buyval A, and Longhurst B (2015) PBS level 3 and 4 standards review, Austroads.

CTRE (Center for Transportation Research and Education) (1996) *The potential for performance-based standards as the basis for truck size and weight regulation in the United States*, CTRE.

de Pont J, Baas P, Hutchinson D, and Kalasih D (2002) 'Including performance measures in dimensions and mass regulations', *7th International Symposium on Heavy Vehicle Weights & Dimensions*.

de Saxe CC, Kural K, Kharrazi S, Schmidt F, Van Geem C, Berman R, Woodrooffe J, and Cebon D (2019) 'FALCON III: defining a performance-based standards framework for high capacity vehicles in Europe', *HVTT15*.

Ervin RD and Guy Y (1986) *The influence of weights and dimensions on the stability and control of heavy-duty trucks in Canada*, National Highway Traffic Safety Administration.

Germanchev A (unpublished) *Roll stability control (RSC) in a PBS lane change manoeuvre*, National Transport Research Organisation.

Ghoneim, A & Fays, R 2007, Development of vehicle rollover stability control systems at Ford Motor Company, SAE Technical Paper 2007-01-0136, SAE International, Warrendale, PA.

Glaeser KP and Ritzinger A (2012) 'Comparison of the performance of heavy vehicles results of the OECD study: 'moving freight with better trucks'', *Transport Research Arena - Europe 2012*.

ISO (International Standards Organisation) (2000) *ISO 14791:2000. road vehicles – heavy commercial vehicle combinations and articulated buses – lateral stability test methods*, ISO.

Kharrazi S and Thomson R (2008) *Analysis of heavy truck accidents with regard to yaw and roll instability - using LTCCS database*, Chalmers University of Technology.

Kharrazi S, Karlsson R, Sandin J, and Aurell J (2015) 'Performance based standards for high capacity transports in Sweden', *FIFFI project 2013-03881 - Report 1 Review of existing regulations and literature*.

Meuller TH, de Pont J, and Baas PH (1999) *Heavy vehicle stability versus crash rates*, Transport Engineering Research New Zealand Limited.

MRWA (Main Roads Western Australia) (2021) *WA performance based standards (PBS) scheme standards and vehicle assessment rules*, MRWA.

NHVR (National Heavy Vehicle Regulator) (2022) *Performance-based standards scheme - the standards and vehicle assessment rules*, NHVR.

NRTC (National Road Transport Commission) (1999) *Performance based standards for heavy vehicles in Australia field of performance measures December 1999*, NRTC

NRTC (National Road Transport Commission) (2000) *Specification of performance standards and performance of the heavy vehicle fleet (performance-based standards - NRTC/Austroads project A3 and A4) discussion paper August 2000*, NRTC

NTC (National Transport Commission) (2011) *Performance based standards regulatory impact statement March 2011*, NTC.

NTC (National Transport Commission) (2017) *Assessing the effectiveness of the PBS Scheme discussion paper August 2017*, NTC.

NTC (National Transport Commission) (2018) *Reforming the performance-based standards scheme policy paper May 2018*, NTC.

NTC (National Transport Commission) (2024) *Australian Code for the Transport of Dangerous Goods by Road & Rail Edition 7.9 Volume I*, NTC.

Pape D, Arant M, Hall D, Nelson S, Petrolino J, Franzese O, Knee H, Yeakel S, Hathaway R, Keil M, and Pollock P (2009) *U02: heavy truck rollover characterization (phase-A) final report*, National Transportation Research Center, Incorporated.

Pape D, Arant M, Brock W, Delorenzis D, LaClair T, Lim A, Petrolino J, and Spezia A (2011) *U31: vehicle stability and dynamics electronic stability control final report*, National Transportation Research Center, Incorporated.

Parker S (2004) *An alternative measure for evaluating the dynamic performance of heavy vehicles*, Forest Engineering Research Institute of Canada.

Prem H, Ramsay E, McLean J, Pearson B, de Pont J, Woodrooffe J, and Yeo D (2001) *Report on initial selection of potential performance measures (performance-based standards - NRTC/Austroads project A3 and A4) discussion paper January 2001*, NRTC.

Prem H, Ramsay E, McLean J, Pearson B, Woodrooffe J, and de Pont J (2001) *Definition of potential performance measures and initial standards (performance-based standards - NRTC/Austroads project A3 and A4) discussion paper March 2001*, NRTC.

Prem H, Ramsay E, McLean J, Pearson B, Woodrooffe J, and de Pont J (2001) *Definition of potential performance measures and initial standards (performance-based standards - NRTC/Austroads project A3 and A4) discussion paper April 2001*, NRTC.

Prem, H, Ramsay, E, McLean, J, Pearson, B, Woodrooffe, J & de Pont J (2001) *Report on workshops on performance-based standards (performance-based standards - NRTC/Austroads project A3 and A4) workshop report December 2001,* NRTC.

Prem H, de Pont J, Pearson B, and McLean J (2002) *Peformance characteristics of the Australian heavy vehicle fleet (performance-based standards - NRTC/Austroads project A3 and A4) discussion paper February 2002*, NRTC.

SAE International (1993) *A test for evaluating the rearward amplification of multi-articulated vehicles*, SAE International.

Sharp K and Prem H (2001) *Report on workshops on performance-based standards (performance-based standards - NRTC/Austroads project A3 and A4) workshop report December 2001*, NRTC.

Sweatman PF (1993) *Overview of dynamic performance of the Australian heavy vehicle fleet technical working paper no. 7*, NRTC.

Taramoeroa N and de Pont J (2009) *Optimisation of heavy vehicle performance September 2009*, NZ Transport Agency.

Winkler CB, Fancher PS, Bareket Z, Bogard S, Johnson G, Karamihas S, and Mink C (1992) *-Heavy vehicle size and weight- test procedures for minimum safety performance UMTRI-92-13*, The University of Michigan Transportation Research Institute.

Winkler CB and Ervin RD (1999) *Rollover of heavy commercial vehicles UMTRI-99-19*, The University of Michigan Transportation Research Institute.

Woodrooffe J, Blower D, Gordon T, Green PE, Liu B, and Sweatman P (2009) *Safety benefits of stability control systems for tractor-semitrails final report*, National Highway Traffic Safety Administration.

Woodrooffe J, Bereni M, Germanchev A, Eady P, Glaeser KP, Jacob B, and Nordengen P (2010) *Safety, productivity, infrastructure wear, fuel use and emissions assessment of the international truck fleet a comparative analysis*, Joint Transport Research Centre.

Zheng X, Chen Y, and Ahmadian M (2023) 'Interconnected roll stability control system for semitrucks with double trailers', *SAE Technical Papers - April 2023*.