Formalising the PBS System in New Zealand

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Abstract

Traditionally size and weight regulation has been based primarily on prescriptive limits. Since the 1980s there has been increasing interest in using Performance-Based Standards (PBS) as a mechanism for regulating size and weight. New Zealand was an early adopter of the PBS approach and performance assessment has been used extensively both to inform the development of the prescriptive limit regime and to evaluate over-dimension and over-weight vehicles for permit operations. The performance measures and standards used in New Zealand for these purposes have primarily been those developed originally for the Road Transport Association of Canada (RTAC) study in the 1980s and more recently those developed for the Australian PBS system. These performance standards reflect the conditions and requirements of the jurisdictions in which they were developed and are not necessarily appropriate in New Zealand. This paper presents the development of a set of performance standards that reflect the New Zealand situation.

1

1. Introduction

The traditional method of regulating vehicle configuration, vehicle size and weight has been through the use of prescriptive limits. Thus, for example, we have limits for the maximum height, width and length of vehicles as well as limits on axle weight, axle group weight and gross vehicle weight. Originally the main purpose of size and weight regulations was to protect the infrastructure. In recent times, size and weight regulations have also been used to try to improve vehicle safety, while balancing between the efficient operations of the heavy vehicle fleet within the constraints imposed by the road network.

An alternative approach to prescriptive limits is the use of performance-based standards (PBS). A performance measure consists of a prescribed test procedure during which some defined quantity is measured. A performance-based standard additionally defines acceptability levels for the performance measure. The use of PBS for regulating motor vehicles is not new. For example, one of the braking requirements in New Zealand is defined as a maximum stopping distance from 30km/h. This is a performance-based standard and it dates back to the late 1920s. Similarly there is a rollover stability requirement for buses in the UK that dates back to the 1920s. However, these are isolated performance standards relating to a specific aspect of vehicle performance rather than a system of performance-based standards for characterising the whole vehicle.

In the 1970s and 1980s, researchers at the University of Michigan Transportation Research Institute (UMTRI) undertook a number of studies investigating the factors influencing heavy vehicle performance (Bernard, Fancher et al. 1973, Fancher, Bernard et al. 1973, Winkler, Bernard et al. 1976, Fancher, MacAdam et al. 1977, Ervin, Fancher et al. 1978, Winkler and Fancher 1981, Ervin and MacAdam 1982, Winkler, Fancher et al. 1983, Fancher, Ervin et al. 1984). To characterise this vehicle performance they developed a number of performance measures. From these individual performance measures, the concept of using a set of PBS for characterising vehicles was developed in a study undertaken for the Road Transport Association of Canada (RTAC 1986).

Following the publication of the RTAC study, New Zealand was one of the first jurisdictions in the world to start using the PBS as a guide for assisting in the development of size and weight regulations. Subsequently some of the PBS were used as a basis for permitting vehicles outside of the standard size and weight limits. In 2002 the size and weight regulations were moved into the Vehicle Dimensions and Mass (VDAM) Rule (Land Transport Safety Authority 2001). Again PBS were used to develop some aspects of the Rule and most notably a rollover stability performance standard applying to nearly all large heavy vehicles was incorporated in the Rule.

In 2010, there was an amendment to the VDAM Rule which provided for the introduction of High Productivity Motor Vehicles (HPMVs) (New Zealand Transport Agency 2010). This amendment provided for vehicles to be permitted to exceed the standard size and weight restrictions on the sections of the network that could safely accommodate them. To facilitate the uptake of HPMVs, the NZTA in conjunction with the transport industry promoted the concept of pro-forma designs for larger and heavier vehicles that could fit on the existing network. The pro-forma designs were developed using PBS and essentially are larger vehicles which have key dimensions constrained within a range which ensures that satisfactory performance is achieved. HPMVs have also been permitted on a one-off basis

where they have been individually assessed to ensure that they have comparable or better performance than the pro-forma designs.

Although PBS has been used extensively in managing size and weight in New Zealand a formalised PBS system does not exist. PBS has been recognised as a useful tool to guide the regulator to transparently balance productivity and safety limits. Initially the performance measures used were based on those defined by UMTRI and the RTAC study. More recently, since the establishment of the PBS regime in Australia in 2008, the Australian measures have also been used. There have also been some New Zealand specific performance measures used. Although this approach appears to be rather ad hoc, it has for the most part worked reasonably well in the context that PBS has been used in New Zealand. In many of the applications specific aspects of performance were identified as being critical and the analysis was based on comparing the performance with that of existing vehicles that were considered acceptable. Thus the emphasis was on comparative performance rather than absolute performance. Where absolute performance was used, the acceptability levels were largely based on those used overseas although some were adapted for New Zealand.

The HPMV provisions are leading to greater levels of innovation in vehicle configuration design aimed at increasing productivity while still achieving acceptable performance. The VDAM Rule is currently being reviewed and as part of this review the set of PBS applicable to New Zealand is being formalised. This process is considering which performance measures are most relevant to New Zealand and what the appropriate pass/fail criteria should be.

2. PBS Internationally

The first, and to date only, comprehensive PBS system that can be used as an alternative compliance regime to the prescriptive limits regime is that developed in Australia in the early 2000s and which came into operation in 2008. The Australian PBS system in a slightly modified form has been used in South Africa for a trial programme. Most of it is also used in New Zealand for reviewing HPMV permit vehicles.

The Swedish government is currently undertaking a large research project investigating the use High Capacity Transport (HCT) in Sweden. Part of this project is the development of a PBS regime suitable for evaluating these vehicles in a Swedish road transport environment. There are a number of papers on this project at this symposium.

3. Principles of the New Zealand PBS System

The ultimate aim of the project is to create a formalised New Zealand PBS system which can be referenced from the VDAM Rule. This New Zealand PBS system will be based on performance measures that have been developed elsewhere but adapted to the specific conditions found in New Zealand. Furthermore we will be using the experience of other jurisdictions to try to keep the system simple and cost-effective while still being robust. One of the NZ guiding principles is to use PBS to help standardise the fleet and to keep up with technology improvements, but in a way that avoids increasing the number of "orphan" vehicles.

The Australian PBS is the most well-established in the world and so the Australian experience in both developing and using a PBS system provides valuable insights into some of the major issues. The development of the Australian PBS system was based on a philosophy of having

no prescriptive limits at all and so the aim was to define all of the vehicle requirements in terms of performance. In practice this was not able to be achieved (de Pont 2014). PBS vehicles in Australia are still subject to a number of prescriptive requirements such as height, width and length which are determined by infrastructure limits and traffic engineering considerations rather than vehicle performance. Prescriptive limits like this are unambiguous and simple to evaluate. If they are unavoidable this should be accepted. As well as this there are some performance standards such as startability, gradeability and acceleration capability that can be defined reliably using prescriptive requirements. These two principles are used in defining the New Zealand PBS system:

- Prescriptive limits that are determined by the requirements of the infrastructure and traffic engineering issues rather than vehicle performance are specified as prescriptive requirements.
- Vehicle performance characteristics that can be reliably specified by prescriptive requirements are specified as such.

This approach reduces the number of performance measures to be evaluated and provides clear guidance to vehicle designers on the absolute limits they must work within.

One of the regulatory principles in the development of the Australian PBS was that all of the performance measures should be able to be evaluated by physical measurement as well as computer simulation (Prem, Ramsay et al. 2001) and this principle was used to eliminate some measures and to include others. Although all of the performance measures considered can theoretically be evaluated experimentally, in some cases the instrumentation and/or test venue requirements are such that it would be a very expensive exercise. Some performance measures were eliminated because of the difficulty of measuring them experimentally but others that were retained are equally difficult to measure experimentally. All full PBS assessments that we are aware of have been undertaken using computer simulation. In some cases these have been supplemented by experimental testing to validate some aspects of performance or of the modelling. Thus, for the New Zealand PBS system we have not limited ourselves to performance measures that can readily be assessed experimentally. Effectively we have assumed that the PBS assessments will be done by computer simulation. This does still leave scope for the computer simulation model to be validated by experiment and this could be required if there is reason to doubt the results.

The final step in this process was to determine appropriate pass/fail criteria for the performance measures in New Zealand. Ideally these should be based on good evidence for the safety implications of each performance measure. However, for most performance measures, reliable data is not available. Even if the data is available, it is difficult to compare the effect of changes for different performance measures. For example, an increase in low speed swept width will increase the risk of collisions during low speed turns, while a reduction in static rollover threshold increases the risk of rollover crash. How does a 10% increase in the first risk compare with a 10% increase in the second risk? The choice of pass/fail criteria was based on the performance of existing vehicles and international practice.

4. PBS Requirements for New Zealand

4.1 Prescriptive Requirements

The limitations of the infrastructure impose certain size and weight constraints on all vehicles. Over time these limits may be modified as the infrastructure is upgraded. However, because these constraints are imposed by the infrastructure rather than by vehicle performance, it is expected that these requirements will apply to PBS vehicles as well. These limits are:

- Vehicle width
- Vehicle height
- Vehicle overall length
- Axle weights and axle group weights
- Axle spacing
- Combined axle set weight and spacing limits
- Tyre size and pressure

All of these requirements are specified in the VDAM Rule and cannot be violated based on a PBS assessment. A partial exception applies to vehicle overall length where a higher limit (23m) has been used for high productivity motor vehicles compared to the standard legal vehicle limit of 20m. This length limit can potentially be exceeded for a route-specific permit where the route has been assessed for it capacity to cope with longer vehicles.

4.2 Drivetrain Requirements

It is proposed that the drivetrain performance requirements will be specified in terms of prescriptive limits. These should deliver the desired level of performance.

For this approach the following parameters need to be known:

M = gross combination weight at which the vehicle will be operating (tonnes)
W_{drive} = total weight on the drive axle(s) (tonnes)
T_{clutch} = clutch engagement torque (Nm)
T_{peak} = peak engine output torque (Nm)
G_{low} = lowest gear ratio
G_{high} = highest gear ratio
D_{final} = final drive ratio or differential ratio
P_{peak} = peak engine output power (kW)
Ω_{peak} = engine speed at peak power (rpm)
R = rolling radius of drive axle tyres (m)

Assuming that the transmission system has 95% efficiency, the proposed requirements are:

$$W_{drive} \geq 0.25.M$$

This ensures that the drive axles can transmit the required level of tractive forces onto the road. It needs to be evaluated with the vehicle full loaded and empty. The assessor also needs to consider whether there are any critical partial load situations that can occur in normal operations.

$$T_{clutch} \geq \frac{1859.M.R}{G_{low}.D_{final}}$$

This is the startability criterion. It needs to be evaluated with the vehicle fully loaded.

$$T_{peak} \geq \frac{2169.M.R}{G_{low}.D_{final}}$$

This is a low speed gradeability criterion. It needs to be evaluated with the vehicle fully loaded.

$$P_{peak} \geq 75.2 + 4.59M$$

This is a high speed gradeability criterion. It needs to be evaluated with the vehicle fully loaded.

$$\frac{0.12.\Omega_{peak}.\pi R}{G_{high}.D_{final}} \geq 90$$

This criterion ensures that the gearing is high enough for the vehicle to exceed 90km/h. It is unlikely that this condition will ever be critical. It is independent of load.

These drivetrain requirements do not include an acceleration requirement as is the case in Australia. If the above power and torque requirements are met, the acceleration capability will be satisfactory unless the gear ratios are very poorly matched to the engine's torque characteristics.

4.3 Low Speed Turning Performance

The proposed primary low speed turning test manoeuvre is the same one that is used in the Australian PBS system (National Transport Commission 2007). The specified path consists of straight tangent approaches to a 90° circular arc of 12.5m radius. The vehicle must traverse the path at a speed no greater than 5km/h with the outermost point of the forward most outside steered wheel following the specified path to within ±50mm. This test should be undertaken with the vehicle laden and unladen.

Swept Width
During this manoeuvre the paths of innermost and outermost points of the vehicle are traced. The distance between these two paths is the swept width and the maximum value of the swept width is the performance measure. This is illustrated in Figure 1 below.
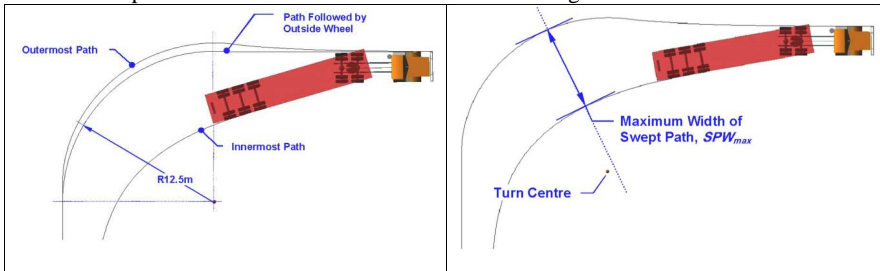
Figure 1.   Illustration of the swept width performance measure reproduced from (National Transport Commission 2007)
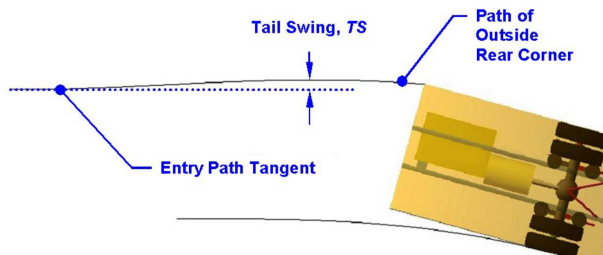
The proposed low speed swept width standard is:

Maximum width of swept path ≤ 7.0m

This threshold is lower than the Australian PBS level 1 limit and reflects the performance of the largest vehicles currently operating on the New Zealand network.

Tail Swing

This measure is identical to that used in the Australian PBS system as illustrated in Figure 2.

Figure 2. Tail swing as prescribed in the Australian PBS system (National Transport Commission 2007).

The tail swing is defined as the maximum excursion of the rear outermost corner of the vehicle outside the entry and exit path tangent. The proposed performance standard is the same as that used in Australia:

Maximum tail swing ≤ 0.30m

Frontal Swing

The frontal swing behaviour is analogous to tail swing and is the result of front overhangs. It occurs at the end of the turn. Both the towing vehicle and the trailer(s) can exhibit frontal swing. This is illustrated in Figure 3. The frontal swing is the maximum excursion of the front outermost corners of the vehicle outside the exit path tangent. The proposed performance standard for frontal swing is:

Maximum frontal swing ≤ 0.75m   for trucks and trailers
Maximum frontal swing ≤ 1.50m   for buses
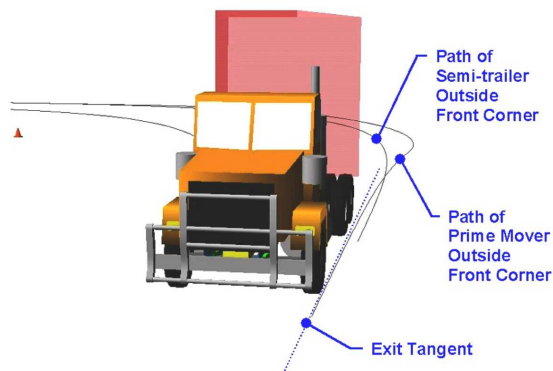
Figure 3. Frontal swing behaviour of a tractor semitrailer combination (National Transport Commission 2007).

This differs somewhat from the Australian requirements which are quite complicated for trailers and can produce some perverse outcomes if this risk is not recognised. For example, in some cases, the performance of the trailer can be improved by simply worsening the performance of the tractor.

Steer-Tyre Friction Demand
The low speed turning performance measures are based on keeping the vehicle speed low enough that there is no significant lateral acceleration and thus vehicle tyres do not need to produce any net sideways force. However, if the vehicle is fitted with axle groups, these axles will have a tendency to go straight ahead and thus the steer tyres have to generate the cornering forces needed to make these axle groups turn. If they cannot generate enough cornering force the vehicle will tend to "sledge" straight ahead particularly in situations where the road friction is reduced such as rain, snow or loose gravel. The steer-tyre friction demand measure quantifies the lateral force demand on the steer tyres as a proportion of the weight on the steer tyres. Effectively this the minimum level of tyre-road friction required for the vehicle to be able to steer. The performance measure is defined as:

$$Steer\ tyre\ friction\ demand = \frac{\sum_{n=1}^{N} \sqrt{F_{xn}^2 + F_{yn}^2}}{\sum_{n=1}^{N} F_{zn}^2}$$

where: F_{xn} = longitudinal tyre force at nth tyre (N)
          F_{yn} = lateral tyre force at nth tyre (N)
          F_{zn} = vertical tyre force at nth tyre (N)
          N = number of tyres on the steer axle or axle group

The proposed performance standard for steer tyre friction demand is:

Steer tyre friction demand ≤ 0.50

This performance standard differs from the equivalent Australian PBS standard in that it does not incorporate the available road-tyre friction. In the Australian system requirement is defined as a percentage of the available road-tyre friction and thus there is the potential for

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requirement to vary for different road surfaces. In practice the road-tyre friction is assumed to be 0.8 and so this simply becomes a scaling factor. We have simply embedded the scaling factor in the requirement.

Steady State Low Speed Swept Width

The low speed swept width measure evaluated using the 90° turn does not represent the maximum low speed swept width for long combination vehicles because, with a 12.5m radius, these vehicles require more than 90° of turn angle to achieve maximum off-tracking. For normal intersection turns, the 90° turn is sufficiently representative to control this aspect of performance but for longer lower speed highway curves such as those marked with 25km/h or 35km/h advisory speed signs, the vehicles can achieve steady state off-tracking and thus it is important to also control this aspect of performance.

The proposed test manoeuvre for this performance standard is a 25m radius wall-to-wall turn as described in EC (1992). The turn should be sufficiently long that steady state off-tracking is achieved. The performance measure is swept width which is measured in exactly the same way as the swept width for the 90° turn shown in Figure 1.

The proposed steady state low speed swept width performance standard is:

> Maximum width of swept path ≤ 5.25m

4.4   Steady State High Speed Directional Performance

High Speed Steady State Off-tracking

During high steady speed turns vehicles off-track on the outboard side. That is, the path of the rear axles is outboard of the path of the front axles. This increases the road width required by the vehicle. Excessive high speed off-tracking can result in the rear outside tyres going off the edge of the road during the turn. The magnitude of this off-tracking depends on the vehicle configuration and loading, the curve radius and the vehicle speed. Because the tyre characteristics are not linear, we cannot simply scale the speed effect. Thus this performance standard assesses the high speed off-tracking at two speeds on the same radius curve.

The test manoeuvre is a 319m radius turn of sufficient length to achieve steady state behaviour. The vehicle undertakes the manoeuvre at 90km/h and at 100km/h. These speeds generate lateral accelerations of 0.2g and 0.25g respectively. These lateral accelerations are below the level at which rollover will occur (see static rollover threshold requirements) but are both faster than recommended driving practice. For an 85km/h advisory speed curve undertaken at 85km/h, the lateral acceleration is 0.18g. The NZTA recommended practice for heavy vehicles is to go at 10km/h less than the advisory speed which would result in a lateral acceleration of 0.14g.

The high speed off-tracking is defined as the maximum distance between the path of the centre of the front steer axle and the path of the worst case rear axle. This may be the last axle but is sometimes the second to last axle.

The proposed steady state high speed off-tracking standard is:

> High speed off-tracking at 90km/h ≤ 0.46m
> High speed off-tracking at 100km/h ≤ 0.68m

This standard is not included in the Australian PBS system. Some aspects of it are covered by the "Tracking Ability in a Straight Path" standard but this based on very low levels of lateral acceleration (0.03g) where the tyres are operating in the linear range.

Static Rollover Threshold
The static rollover threshold is the maximum lateral acceleration that the vehicle can withstand before the onset of rollover. The onset of rollover is defined as the point where all of the axles except the steering axles on one side of the vehicle have lifted off the ground. Currently most large heavy vehicles in New Zealand are required to achieve a static rollover threshold of 0.35g. New HPMVs are additionally required to be fitted with Roll Stability Control (RSC) or older units in new HPMV configuration to achieve a static rollover threshold of 0.40g.

The proposed manoeuvre used to evaluate this performance measure by computer simulation is the ramp steer manoeuvre used in the RTAC study (RTAC 1986). Static rollover threshold may also be determined by physical testing using a tilt table test. The requirements for undertaking a tilt table test are laid out in SAE Recommended Practice Guide J2180 (SAE 1998). A tilt table test must follow this procedure or some alternative international guidelines acceptable to the NZTA. There are currently no suitable tilt tables in New Zealand.

Combinations of units within a vehicle that are roll-coupled (i.e. connected by a turntable or a standard fifth wheel) will roll together while vehicle units that are not roll-coupled (i.e. connected by a pin coupling) will roll independently. Rollover is deemed to have occurred when any vehicle unit or group of units that can roll independently has achieved wheel lift-off. Note that for trucks and tractors, the steer axles do not have to lift-off in order for the onset of rollover to be deemed to have occurred.

When the rollover unit is a group of vehicle units, such as a B-train, each of the vehicle units will have a slightly different lateral acceleration at the point of wheel lift-off. To determine the static rollover threshold we use a weighted average of these lateral accelerations calculated as follows:

$$AY_{rcu} = \frac{\sum m_i h_i AY_i}{\sum m_i h_i}$$

where: AY_{rcu} = resultant lateral acceleration of the roll-coupled units (m/s²)

m_i = sprung mass of vehicle unit i (kg)

h_i = height of sprung mass centre of gravity of vehicle unit i (m)

AY_i = lateral acceleration of sprung mass centre of gravity of vehicle unit i (m/s²)

The proposed static rollover threshold standard for acceptable performance is:

> Static Rollover Threshold ≥ 0.35g

This is in line with current requirements for almost all large heavy vehicles in New Zealand.

4.5 High Speed Dynamic Performance

Undertaking a high speed evasive manoeuvre with a combination vehicle generally results in an amplified response at the rear of the vehicle. This causes a load transfer from one side of

the vehicle to the other which, if it is severe enough can cause rollover. Typically the path of the rear vehicle unit off-tracks outside the path of the towing vehicle. The following three performance standards are designed to control this behaviour.

The manoeuvre used for these three performance standards is the high speed lane change manoeuvre defined in (ISO 2000). This is a 1.46m sinusoidal lane change executed in 2.5 seconds. The path is the path of the steer axle and it generates a peak lateral acceleration at the steer axle of 0.15g.

Load Transfer Ratio
The load transfer ratio calculation is undertaken for each set of roll-coupled units within the vehicle. The load transfer ratio is defined as:

$$\text{Load Transfer Ratio} = \frac{\left|\sum (F_L - F_R)\right|}{\sum (F_L + F_R)}$$

where: F_L = vertical load on tyres on left side of vehicle (N)

F_R = vertical load on tyres on right side of vehicle (N)

The steer axle(s) is omitted from the computation due to its low roll stiffness and negligible influence on load transfer. Note that this performance measure is zero when the vehicle is stationary on level ground and rises to one when the vehicle is at the point of rollover.

The proposed requirements for the load transfer ratio performance standard is:

Load transfer ratio ≤ 0.7,	if GCW ≤ 50 tonnes
Load transfer ratio ≤ 0.6,	if GCW > 50 tonnes

This performance standard was not included in the Australian PBS system.

Rearward Amplification
During the high speed lane change manoeuvre, the maximum lateral acceleration of the steer axle is 0.15g. This effect is amplified for the trailing vehicles and thus the lateral acceleration of the centre of mass of the trailing units is usually greater than 0.15g. The rearward amplification is defined as:

$$Rearward\ amplification = \frac{max(|AY_{last\ vehicle\ unit}|)}{max(|AY_{steer\ axle}|)}$$

The proposed performance standard for rearward amplification is:

Rearward amplification ≤ 2.0

The Australian PBS system uses a more complicated limit for this standard based on the static rollover threshold. Vehicles with better rollover stability are permitted to have poorer rearward amplification. The proposed New Zealand is the same as the Australian when the static rollover threshold value is 0.35g.

High Speed Transient Off-tracking
At the completion of the lane change manoeuvre, the path of the rear trailer will tend to "overshoot" the path of the towing vehicle as illustrated in Figure 4. Clearly excessive "overshoot" is undesirable.
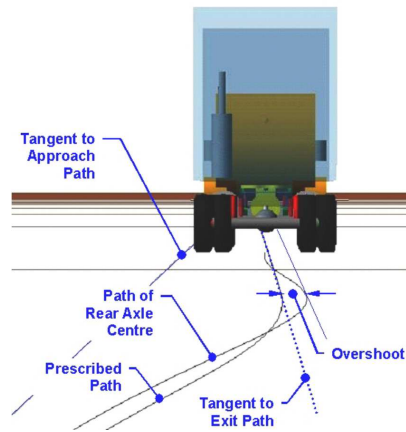
Figure 4. **High speed transient off-tracking at the completion of the lane change (National Transport Commission 2007).**

High speed transient off-tracking is defined as the maximum magnitude of the overshoot beyond the tangent to the exit path of the worst case rear axle.

The proposed performance standard for high speed transient off-tracking is:

High speed transient off-tracking ≤ 0.6m

This is the same as the Australian PBS system limit for level 1 vehicles.

Yaw Damping Ratio

If a sudden sharp steering input is applied in a combination vehicle it will cause the trailers to oscillate from side to side. For safe operations these oscillations should decay rapidly. The yaw damping ratio is a measure of how quickly these oscillations decay.

A pulse steer test manoeuvre is defined in ISO standard 14791 (ISO 2000) but this is quite broad and allows considerable flexibility. (El-Gindy 1995) and Austroads (Prem, Ramsay et al. 2000) propose using a ±3.2° pulse steer input at the wheels with a period of 0.1s while travelling at 100km/h. These parameters are compatible with the requirements of ISO 14791 and thus we will specify this as the manoeuvre. The procedure for calculating the yaw damping ratio is described in detail in (National Transport Commission 2007).

The proposed performance standard for yaw damping ratio is:

Yaw damping ratio ≥ 0.15

5. Conclusions

The draft set of performance standards for New Zealand has been formulated and prepared for future industry consultation. Some aspects of the performance standards will be included in the new Vehicle Dimensions and Mass Rule under preparation and policy consideration is

being given to future coverage of the draft PBS standards. The finalisation of the New Zealand PBS requirements will now occur over the next year or so.

The proposed PBS standards are largely derived from standards that have been used in other jurisdictions. These have been adapted to reflect New Zealand conditions. There are some fundamental differences between the approach used in developing these standards and that used for the Australian PBS system. The first is that it is accepted that some prescriptive requirements will be imposed upon the vehicles because of limitations in the capacity of the infrastructure. There is no attempt to reformulate these requirements in terms of performance standards. Secondly, some performance standards can be achieved by specifying prescriptive requirements. This is simpler to apply and easier to check so, where possible, this has been done.

For the remaining performance standards, the proposed pass/fail criteria have been determined based on the performance characteristics on existing New Zealand vehicles and international practice. These may yet be refined in the consultation process. As a general principle, there is no absolute right answer. Allowing more liberal pass/fail criteria typically increases the safety risk but provides more flexibility in vehicle configuration and vice-versa. In most cases the safety risk implications are difficult to quantify. Basing the criteria on the performance of the existing fleet implies no degradation in safety. Generally the NZTA has imposed additional requirements on HPMVs so that their safety performance is superior to that of the existing fleet.

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