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Review of Tyre Management Practice in the Australian PBS System

Discussion Paper

Prepared for:

NHVR

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EXECUTIVE SUMMARY

The author has been engaged by the National Heavy Vehicle Regulator (NHVR) to undertake a review of the management of tyres in the Performance Based Standards (PBS) scheme. Tyres are consumable items but their characteristics can have a significant effect on some aspects of vehicle performance. This causes a number of issues. Vehicle certifications are often based on specific makes and models of tyres. However, the availability of these tyres varies by geographic location and over time. Tyre models are superseded by new models and so operators can find it difficult to source the approved tyre when a replacement is needed. Furthermore, different tyre testing technologies generate significantly different results for the same tyre. Clarification of the tyre data is necessary to ensure that PBS assessments completed by computer simulation align with real world vehicle performance and also that assessments using different software packages are comparable.

This review is required to be independent and industry focussed and to provide a recommended approach to resolving the identified issues that will be supported by the majority of the industry. Given these requirements for an industry focus and for the recommendations to achieve, at least, majority support it is essential consult extensively with the key stakeholders. This document represents the first stage of the formal stakeholder consultation process.

This discussion paper provides a broad overview of the state of knowledge of how tyres behave and what the key tyre characteristics are in relation to the performance measures in the PBS scheme. The tyre properties discussed are:

- Inflation Pressure
- Vertical Stiffness
- Lateral Force and Aligning Moment
- Relaxation Length

The paper then discusses how these tyre characteristics are measured to generate input data for the simulation analyses. This is a critical issue because there are substantial differences in the results lateral force and aligning moment from different testing technologies and testing procedures. This means that two assessors assessing the same vehicle with the same tyres using the same software can get substantially different results for some PBS standards if they obtain their tyre data from different sources.

Because the lateral force and aligning moment are measured as an array of data points for a range of vertical loads and slip angles, no two tyres will be exactly the same. Thus we reviewed two classification schemes that are designed to group similar tyres together so that a given PBS assessment could apply to a selection of tyre makes and models rather that to just one.

Finally we propose four options for the way forward and discuss the pros and cons of these. The four options are:

- Establish a centralised database of tyre data
- Specify one set of generic tyres for all assessments
- Non-hierarchical classification system
- Hierarchical classification system

It should be noted that the options proposed are not the only possibilities. It is possible to create hybrids of these options or to propose something completely different. In fact, both the classification system approaches will work better if they are operated in conjunction with a centralised database.

At this time, we are expressing no preference for any of the options outlined. Our views on the preferred options will be informed by the stakeholder feedback.

OVERVIEW

The author has been engaged by the National Heavy Vehicle Regulator (NHVR) to undertake a review of the management of tyres in the Performance Based Standards (PBS) scheme. Since assuming responsibility for the PBS scheme in 2013, NHVR has received numerous representations from a range of stakeholders about issues relating to PBS tyres. These issues cover a wide range of issues that span the life of a PBS vehicle, from the data and testing requirements during the design and assessment of a PBS vehicle, to the in-service maintenance and use of PBS vehicles and combinations. Tyres are consumable items but their characteristics can have a significant effect on some aspects of vehicle performance. In addition, there are no international technical standards that can be easily adopted for the PBS Scheme.

Clarification of the tyre data is necessary to ensure that PBS Assessments completed by computer simulation align with real world vehicle performance and also that assessments using different software packages are comparable.

While the NHVR and industry have undertaken significant amounts of work in an attempt to resolve these issues, development of an approach that attracted broad support across the various stakeholders has not been possible. This review is required to be independent and industry focussed and to provide a recommended approach to resolving the identified issues that will be supported by the majority of the industry.

Given these requirements for an industry focus and for the recommendations to achieve, at least, majority support it is essential consult extensively with the key stakeholders. This document represents the first stage of the formal stakeholder consultation process.

The NHVR publication prepared by the National Transport Commission entitled "PBS Scheme - The Standards and Vehicle Assessment Rules" sets out the minimum detail of tyre properties that needs to be included when undertaking PBS assessments. These vary from vary between the different performance standards but for the PBS scheme as a whole they are:

- Vertical stiffness – the stiffness that causes normal force to vary with tyre compression.
- Lateral force characteristics in the free-rolling condition – the characteristics that define lateral force as a function of normal force and lateral slip angle.
- Aligning torque characteristics – the characteristics that define aligning torque as a function of normal force and lateral slip angle.

Appendix G specifies the information required to be provided by the assessor for Vehicle Certification. For tyres, this says: tyre size, make and model OR rolling radius, cornering characteristics and vertical stiffness. However, this information has to be in a form that can be checked by the certifier, which favours the size make and model option. Appendix H on "risk sensitive parameters related to vehicle design features" does appear to include an option of using generic tyres. For the standards that are sensitive to tyre characteristics, it says "If generic, non-descript tyres were used in the analysis these should have cornering characteristics that are consistent with worst-case performing tyres of the same size to ensure that any tyre of the same size can be used." There is, of course, a challenge in finding the tyre that has the worst-case performance.

The discussion paper that follows provides a broad overview of the state of knowledge of how tyres behave and what the key tyre characteristics are in relation to the performance measures in the PBS scheme. It then discusses the main issues associated with applying this knowledge of tyre behaviour to PBS assessments and the operations of PBS vehicles. Finally it proposes some options for the way forward and discusses the pros and cons of these. It should be noted that the options proposed are not the only possibilities. It is possible to use combinations of these options or to propose something completely new. Also, at this time, we are expressing no preference for any of the options outlined. Our views on the preferred options will be informed by the stakeholder feedback.

The stakeholder feedback that we are seeking is in three parts:

- The first part relates to the tyre characteristics. Are there any key issues that we have overlooked? Is there anything that you disagree with and, if so, why? Please supply supporting evidence if you can.
- The second part relates to the proposed options. Which ones do you favour? Which ones do you oppose? Please provide reasons in the comments section.
- The final part is an option to propose your own preferred approach. This could be a hybrid of the options already proposed or it could be completely different. Please provide the rationale for your proposal, i.e. why is better than the other options and what are its limitations.

INTRODUCTION

Tyres serve as the only interface between the vehicle and the road surface. Apart from aerodynamic and gravitational forces, all of the other forces acting on the vehicle are transmitted through this interface (Wong 2008). The running gear of a vehicle performs four key functions:

- supporting the weight of the vehicle
- cushioning the vehicle over surface irregularities
- providing sufficient traction for driving and braking
- providing adequate steering control and direction stability

Pneumatic tyres are able to fulfil these functions effectively and efficiently and so they are universally used in road vehicles. To understand the behaviour and performance of road vehicles we need to understand the mechanics of how tyres work to transmit forces between the vehicle and the road.

Note that the mechanics of tyres on hard surfaces such as roads are different to those on deformable surfaces such as soil, gravel or sand. The PBS vehicle assessment process considers only the performance on roads and so this discussion is limited to the behaviour characteristics of tyres on hard surfaces and specifically to the tyre characteristics that affect the vehicle's performance with respect to the PBS requirements.

The pneumatic tyre is flexible with the tread band and sidewalls bending so that an area of the tyre known as the contact patch is in contact with the road surface. The stiffness of the tyre and the magnitude of the contact patch are influenced by the inflation pressure. As the tyre rolls, the contact patch moves around the tyre and so the tread band and sidewalls are continually flexing which causes the tyre to heat up. At the same time the flow of air over the tyre removes heat and so eventually an equilibrium temperature is reached. This equilibrium temperature depends on the ambient air temperature and how hard the vehicle is being driven. The increase in tyre temperature results in an increase in inflation pressure which then reduces the contact patch area. In addition to this the material properties of the tyre change which affects how it responds.

In the past, heavy truck tyres were made using a bias ply construction which means that the "plies" or layers that make up the tyre carcass were laid in a criss-cross pattern. This results in relatively high sidewall stiffness and increased rolling resistance. In 1948, Michelin introduced the radial ply tyre (Wong 2008). In this tyre, the carcass plies are laid radially from bead to bead. A belt of several layers of high modulus material is fitted under the tread. Since the 1980s, radial tyres have become dominant and few, if any, bias ply tyres are now used for on-road heavy vehicles.

In this discussion paper we review the aspects of tyre performance that are critical to the PBS measures and consider how they are measured, how they are modelled, what this means in practice, and how they might be characterised in a classification scheme.

TYRE CHARACTERISTICS

Inflation Pressure

Most of the major tyre manufacturers provide technical data documentation which specifies the recommended inflation pressure for their tyres at different load levels. Table 1 shows the load vs inflation data for 11R22.5 tyres for two tyre manufacturers as downloaded from their US web-sites[1]. The values are

[1] https://commercial.bridgestone.com/content/dam/bcs-sites/bridgestone-ex/products/TechnicalInformation/TBR/2016-pdfs/TBR%20Load%20and%20Inflation%20Tables%202015.pdf

https://www.michelintruck.com/reference-materials/manuals-bulletins-and-warranties/load-and-inflation-tables/#/

identical. For other tyre sizes and for the same tyres on European web-sites where the inflation pressures are given in bar rather than psi, there are differences in the data between manufacturers but these are relatively minor.

Table 1. Load vs inflation pressure 11R22.5 tyres.

Manufacturer	Tyre fitment		Inflation pressure (psi)									
		70	75	80	85	90	95	100	105	110	115	120
			Load per axle (kg)									
Bridgestone	Single	4100	4320	4520	4740	5000	5200	5400	5600	5740	5880	6000
	Dual	7960	8320	8640	9000	9440	9840	10240	10600	10720	10840	10900
Michelin	Single		4320	4520	4740	5000	5200	5400	5600	5740	5880	6000
	Dual		8320	8640	9000	9440	9840	10240	10600	10720	10840	10900

Applying the inflation pressures shown in Table 1 to typical Australian axle groups operating at the maximum weight permitted under General Mass Limits (GML) we get the recommended inflation pressures for 11R22.5 tyres shown in Table 2. Note that these are cold inflation pressures and the actual inflation pressure while operating will be higher.

Table 2. Recommended inflation pressure for 11R22.5 tyres operating at Australian General Mass Limits (GML).

Axle Configuration	Tyre configuration	Legal weight limit (kg)	Recommended inflation pressure (psi)
Single (steer)	single	6000	120
Single	dual	9000	85
Tandem	dual	16500	75
Tridem	dual	20000	~55[i]

[i] In this case the weight per axle is substantially lower than the tabulated values. This value has been estimated by extrapolation.

This implies that, for many vehicle configurations, different inflation pressures should be used for different axle groups. Furthermore, the recommended inflation pressure for unladen or partially laden vehicles is substantially less than that of laden vehicles. Note that this data is one particular commonly used tyre size. It is quite possible to use different tyre sizes on different axles which adds further complications. For example, under Higher Mass Limits (HML) or Concessional Mass Limits (CML), the steer axle can be loaded to 6500kg and thus this 11R22.5 tyre is no longer suitable but it could be replaced by a low profile equivalent with a higher load rating (295/80R22.5 or similar). Note, however, that the maximum allowable tyre pressure in Australia is 825 kPa (120 psi). With a 3250 kg wheel load some of these steer tyre options have a recommended inflation pressure that exceeds the legal maximum. Similarly trailers could be fitted with R19.5 or R17.5 tyres to reduce the load height and improve their rollover stability. The outcome is that each axle group will have its own recommended inflation pressure based on tyre size and tyre load which is likely to different to that of other axles on the vehicle with different tyre loads and/or different tyre sizes.

It would be possible to achieve the recommended tyre pressures on all axles under all load conditions through the use of central tyre inflation (CTI) systems but these are not widely used in Australia currently. CTI is used quite extensively in some sectors such as log transport where reducing tyre pressure for low speed operations off-highway improves traction and reduces the rutting of the “road” surface.

There appears to be a limited amount of data available on tyre inflation practice in Australia. A study was undertaken in Tasmania in the early 1990s (Chowdhury and Rallings 1994). This study recorded inflation pressure and wheel load for 1021 tyres from vehicles stopped for roadside weight inspections. The data from this study show no correlation between wheel load and inflation pressure. The average inflation pressure for standard single tyres was apporximately 740 kPa (107 psi) with the average for steer tyres being a little higher than that of tandem axle or tridem axle tyres. The range of inflation pressures for standard width radials was reported as 600-875 kPa () but about 5% of the measurements were outside of this range with a minimum of 375 kPa and a maximum of 970 kPa. No information was provided on whether there was a difference between the inner and outer tyres of a dual tyre set. These inflation pressure readings were made of "hot" or working tyres and the report notes that these would be expected to be 35-70 kPa higher than the cold inflation pressure. There were also some issues with the calibration of the pressure gauges used and the authors indicated that it is possible that the reported readings are up to 5% too high.

A 2003 US study on tyre condition sensors (Kreeb, Nicosia et al. 2003) included a survey of heavy vehicle tyre inflation practice. This found that nearly 20% of all vehicles had at least one tyre that was underinflated by 20 psi or more. For all tyres, 44% were more than ±5 psi from their target inflation pressure, 7% were underinflated by 20 psi or more and nearly 6% were overinflated by 10 psi or more. They also looked at differences between tyres on the left and right side of the vehicle and the inner and outer position of a dual tyres. Across the whole sample there was no significant difference in inflation pressure between either of these classifications. However, when the looked at the difference in inflation pressure between tyre in the same dual tyre set, they found that about 20% of tractor dual tyre sets and about 25% of trailer dual tyre sets had differences of more than 5 psi between the inner and outer tyres. There is no actual evidence that supports these results being applicable to Australia but there is also no good reason to expect the Australian situation to be substantially different.

Under both NHVAS Maintenance Management and Trucksafe accredition, commercial vehicle drivers in Australia are required to undertake and document a daily walk around check of their vehicle. NHVR has produced guidelines for how to do these checks[2] which specify that the check should establish that the tyres are correctly inflated. Anecdotally, it appears that the tyre inflation checks are typically done by hitting the tyres with a steel bar and listening to the sound, if they are done at all. This method is crude and only approximate but for large combination vehicles, checking all tyres with a tyre pressure gauge would be quite time-consuming.

The effects of under- and over-inflation on the contact patch are illustrated in Figure 1. When the tyre is correctly inflated for the load, the contact pressure is relatively uniform across the contact patch. When the tyre is over-inflated, the area of the contact path reduces and the pressure become less uniform with high pressures in the central region of the tread. This produces a harsher ride and accelerated tread wear in the centre of the tyre. However, it does reduce the rolling resistance of the tyre and should reduce fuel consumption. When the tyre in under-inflated, the area of the contact patch increases and the average pressure decreases. However, the contact pressure is less uniform with higher pressures at the edges of the tread. The tyre is more flexible and thus the rolling resistance increases and the tyre will run hotter. This will result in increased fuel consumption and accelerated tyre wear. Under-inflated tyres are sometimes used in off-road situations at lower speeds to improve traction and reduce rutting.

The reason for this extended discussion on inflation pressure is that the main tyre characteristics that are important for the performance measures in the PBS system are all influenced by it and in a large part this is due the effect that inflation pressure has on the contact patch. These tyre characteristics are typically measured at one, or sometimes two, inflation pressures and usually this is the rated maximum pressure for the tyre. As we have seen, in many cases this would represent an over-inflated tyre and the tyre manufacturers would recommend operating at lower pressure to maximise tyre life and to achieve the best possible performance from the tyres. Thus it is important to consider how the tyre will perform at recommended inflation pressures and, given the evidence of tyres being used at sub-optimal inflation pressures, it would useful to consider what impact this has on performance.

There are technologies, such as CTI, available to facilitate achieving a better match between tyre load and inflation pressure. Applying these to the full could result in every axle group type on the vehicle operating at a different inflation pressure. Taking this into account when modelling the tyres could be very challenging.

[2] NHVR (2018). "Creating heavy vehicle daily checks", https://www.nhvr.gov.au/files/201611-0434-creating-heavy-vehicle-daily-checks.pdf accessed 7 December 2018.

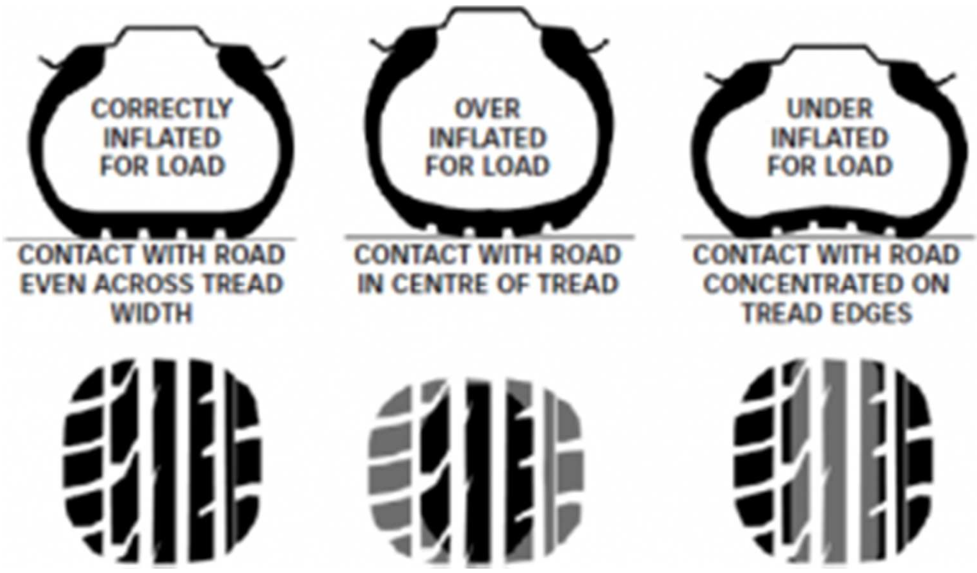

Figure 1. Effects of over- and under- inflation on contact patch.

It has been reported (Anon 2018) that within a dual tyre set differences of in hot inflation pressure between the inner and outer tyres of up to 14 psi are observed even though the cold inflation pressure is identical. This will affect the vertical stiffness of the tyres. For tyres within a dual set, the rolling radius must be equal and so the tyre with the higher pressure will carry more than half of the wheel load while the tyre with the lower inflation pressure will carry less than half. As a result the tyre with the higher wheel load will generate more than half of the cornering and braking forces and therefore will wear more quickly. There are also implications for pavement wear.

Vertical Stiffness

Tyres form part of the vehicle's suspension system. They operate in series with the springs. With two spring elements in series, the combined vertical stiffness of the two is less than the stiffness of either of them and thus the softer spring element has the most effect on the overall vertical stiffness. The situation with regard to roll stiffness is similar although a little more complicated because the roll centres for the sprung and unsprung masses are not the same.

Generally, the vertical stiffness and the roll stiffness contribution of the tyres is higher than that of the suspension and it usually has only a small impact on the performance characteristics of the vehicle. (Fancher, Ervin et al. 1986) indicate that tyre vertical stiffness has a medium effect on rollover stability and no significant effect on either low speed or high speed off-tracking, handling stability, rearward amplification or braking.

The vertical stiffness of the tyres is the slope of the load-deflection curve. This is typically not a straight line thus the instantaneous tyre vertical stiffness varies with load. It is also dependent on the inflation pressure. This relationship to inflation pressure is approximately linear (Besselink, Schmeitz et al. 2010).

Lateral Force and Aligning Moment

Figure 2 shows the axis system that is conventionally used to describe the forces and moments applying to tyres. The angle between the direction of the wheel heading and the direction of wheel travel is known as the slip angle. If this angle is non-zero, the contact patch between the tyre and the road will be distorted and this results in a lateral force as illustrated in Behaviour of a tyre subjected to a side force (Wong 2008) . Note that the relationship between the slip angle and the lateral force is in equilibrium. Each can generate the other and they must balance. Because of the distortion of the contact patch, the lateral force at the road interface does not align with the wheel axis and thus an aligning moment is also generated. Both the lateral force and the aligning moment are dependent on the slip angle and the load on the wheel but these relationships are not linear and not identical. This is illustrated in Figure 4Figure 6 which show the measured cornering force and aligning moment characteristics of the Michelin XZA tyres which were used in the development of the PBS system.

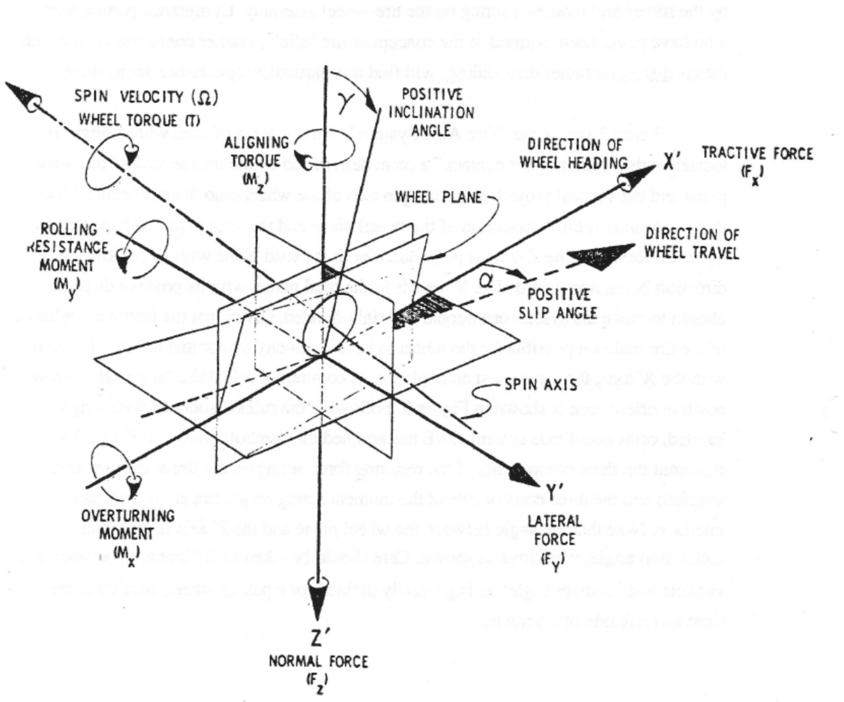

Figure 2. Tyre axis system. (UMTRI 2000).

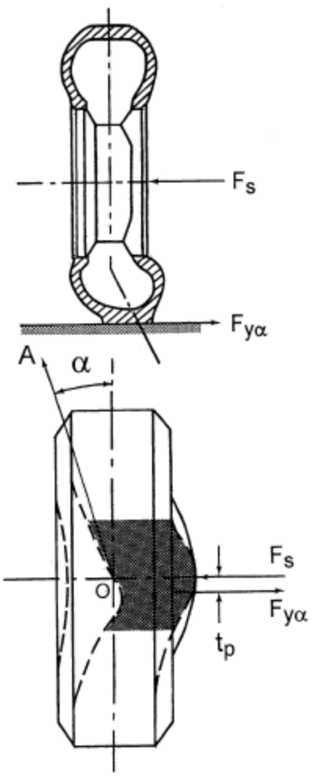

Figure 3. Behaviour of a tyre subjected to a side force (Wong 2008) .

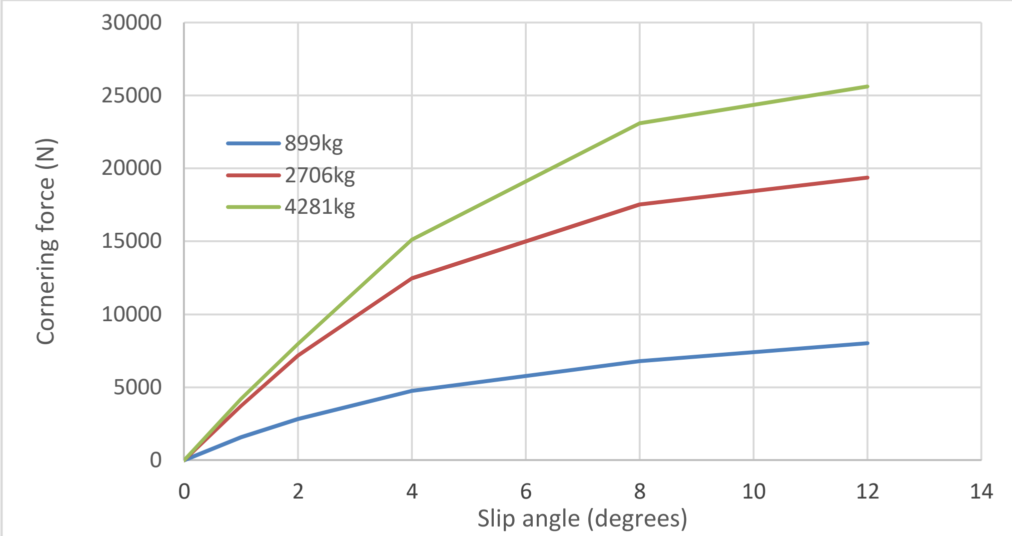

Figure 4. Cornering force vs slip angle for Michelin XZA tyres.

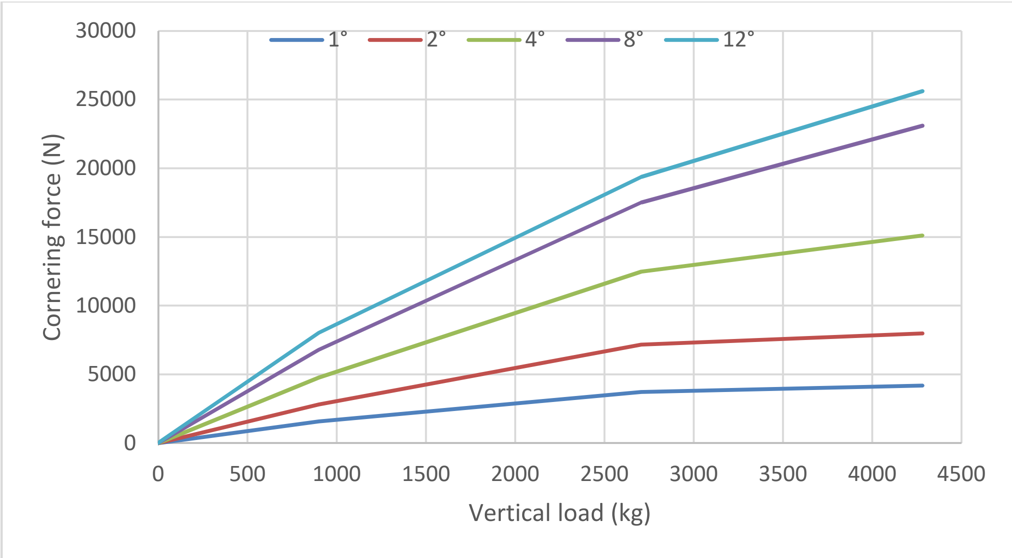

Figure 5. Cornering force vs vertical load for Michelin XZA tyres.

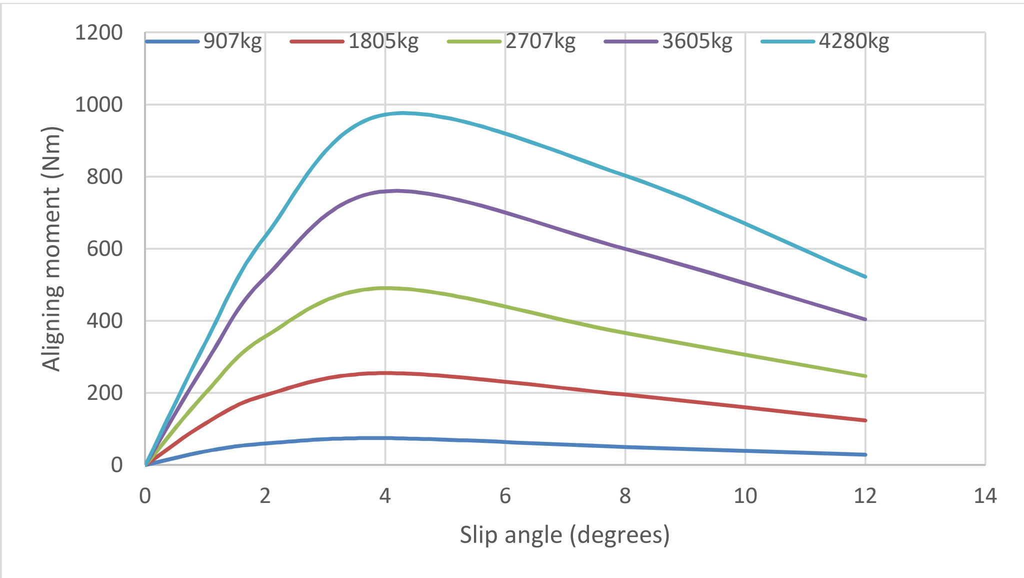

Figure 6. Aligning moment vs slip angle for Michelin XZA tyres.

The force and moment properties of tyres are also affected by the inflation pressure. For heavy truck tyres this relationship is not consistent in shape or magnitude and so no generalisation is possible (UMTRI 2000).

The cornering force response is often characterised by its slope with respect to slip angle at zero slip (the gradient at the origin in Figure 4). This is called the cornering stiffness. The cornering stiffness can then be normalised by the rated load to give the cornering stiffness coefficient. (Fancher, Ervin et al. 1986) identify the cornering coefficient as having a significant effect on high speed off-tracking and rearward amplification. Aligning moment, on the hand, does not have a significant effect on any of the PBS measures.

For small slip angles (less than about 2°) the lateral force and aligning moment response is close to being linear. For normal vehicle operations, small slip angles apply. However, for some vehicle configurations, larger slip angles occur during the low speed turning manoeuvre and during the high speed lane change manoeuvre used in the PBS system and thus the non-linearity can become important.

There is some debate about whether tyre cornering stiffness is affected by tread pattern. Tread patterns are broadly classified as ribbed or blocked (lugged). Some of the literature (Tielking, Fancher et al. 1973, UMTRI 2000) indicates that that tread pattern has very little effect on cornering stiffness on dry surfaces particularly for radial tyres. The ARRB presentation to the July 2017 PBS assessors' meeting indicated that tread pattern was an important factor for classifying tyres.

Wear and aging do significantly affect cornering stiffness but the relative importance of the two factors is not so clear. The literature primarily considers tread wear because aging is more difficult to quantify. (Fancher, Ervin et al. 1986) present cornering stiffness data for Michelin XZA tyres with full tread depth, 50% tread depth and 33% tread depth. The cornering stiffness increases with loss of tread. The 50% tread depth tyre is 19% stiffer than the full tread tyre and the 33% tread tyre is 26% stiffer.

The low speed turning manoeuvre is designed to generate minimal level of lateral acceleration for the vehicle and so the total amount of lateral force required to be generated by the tyres is minimal. On a 2-axle vehicle with Ackerman steering geometry, the tyres operate with zero slip angle. However, when the vehicle is fitted with groups of non-steering axles, it is impossible to achieve a zero slip angle for all of the axles in the group. The magnitude of the slip angles depends on the axle spacing, the turn radius and the number of axles in the group and values of five degrees or more can occur with tridem or quad axle groups but, because the total lateral force is approximately zero, these larger slip angles are matched by slip angles of similar magnitude with the opposite sign on other axles within the group. Provided that all the tyres within the axle group have similar properties, the non-linearity effects are largely cancelled out.

Some lateral forces can be potentially be generated through camber thrust. This occurs when the wheel plane in not perpendicular to the road surface. However, with heavy trucks the wheels are mounted to solid axles and the camber angles are very small, so camber thrust can be ignored (Fancher, Ervin et al. 1986).

In summary, the most important tyre performance characteristic for heavy trucks is cornering force and this varies non-linearly with both wheel load and slip angle. The PBS measures that are significantly affected by the tyre cornering force performance are those derived from the high speed lane change manoeuvre, i.e. rearward amplification (RA) and high speed transient off-tracking (HSTO). Tracking ability in a straight path is also influenced by the tyre characteristics but this involves small slip angles and relatively small changes in wheel load and so the non-linearity of the tyre characteristics is not so important.

Relaxation Length

The cornering forces and aligning moments discussed so far are the steady state values. However, in a dynamic manoeuvre when the slip angles or vertical loads are changing rapidly the tyre response is not instantaneous. This lag in response is usually characterised by the relaxation length which is the distance that the tyre has to move through before the cornering force and aligning moment reach 63% of their steady state values. Note that the relaxation lengths for load changes and slip angle changes are not necessarily the same. The relaxation length can be converted to a time lag by dividing it by the vehicle speed.

(Pacejka 2005) states that the influence of tyre lag on vehicle motion is relatively small and that, at higher values of speed, the effect diminishes and may become negligible although he does note that, for closed loop vehicle control systems, the resulting additional phase lag may affect performance. He also notes that the relaxation length varies with the vertical load.

On the other hand we have anecdotal reports of quite large differences in high speed transient off-tracking (HSTO) for the longer combination vehicles (type 4 road trains etc.) depending on whether or not relaxation length is taken into account in the modelling. These anecdotal reports did not specify the value of relaxation length used. The lane change manoeuvre used for determining HSTO does involve a close loop control driver model and this may be a factor.

The ISO standard (ISO 2000) specifying the lane change manoeuvre for determining HSTO requires that the path of the of the front axle should not deviate from the desired path by more than ±0.15m which is an accuracy that can be achieved by a competent professional driver. However, in developing the Australian PBS system it was found that different simulation software programmes produced significantly different results for the performance measures associated with the lane change manoeuvre and that this was, in part at least, due to differences in the behaviour of the driver model. To reduce these differences between software systems, the Australian PBS system requires that the deviation from the desired path should not be greater than ±0.03m. It is unrealistic to expect a human driver to achieve this level of accuracy for path following although it can be achieved by a driver model in computer simulations. This is usually done by reducing the driver preview time in the model which results in relatively high frequency small steering adjustments. At the speed of the lane change manoeuvre, the time lag due to relaxation length and the driver preview time are of similar magnitude.

A second possibility is that, with very long vehicles that have a relatively large number of axle groups, the effects can accumulate so that a small impact for each axle can be significant for the whole vehicle.

The relaxation length of tyres can be derived from the measurements on some test facilities but it is not routinely reported.

Measuring Tyre Characteristics

In the previous sections we have discussed the key tyre characteristics and the effect that they have on the vehicle's performance as characterised by PBS. The fundamental problem is: how do we measure these tyre characteristics in a way that is consistent, reliable accurate and usable for computer-based assessments.

The SAE has published a recommended practice document for undertaking free rolling cornering tests on truck tyres (SAE 2015). This document is test machine neutral. It also states that the ideal machine, which is one that is capable of fully matching every item in the document, does not yet exist.

There are two fundamental categories of testing apparatus: laboratory machines and "over-the-road" machines. The key difference between the two is that laboratory machines use a simulated roadway which moves in relation to the tyre while the "over-the-road" machines use the actual road surface but need to have a mobility system to move the tyres over the road surface. In both cases the machines need to have a load and positioning system, which can apply vertical loads, slip angles and camber angles to the test tyre and a measuring system which can measure, at a minimum, the applied load, slip angle and test speed as well as the resulting lateral force and aligning moment.

The standard outlines in detail what a good tyre testing regime should look like, including instrument calibration, control tyres, pre-test tyre conditioning, vertical loading, slip angle range, sample sizes and reporting of results. It also specifies the measurement accuracy that an ideal testing facility should achieve.

Laboratory-based testing machines exist in a number of configurations. There are two main classes:

- Roller drum machines
- Flatbed machines

Roller drum machines can be concave or convex as illustrated in Figure 7. Flatbed machines can consist of a moving plank or a belt with a supporting bearing as illustrated in Figure 8.

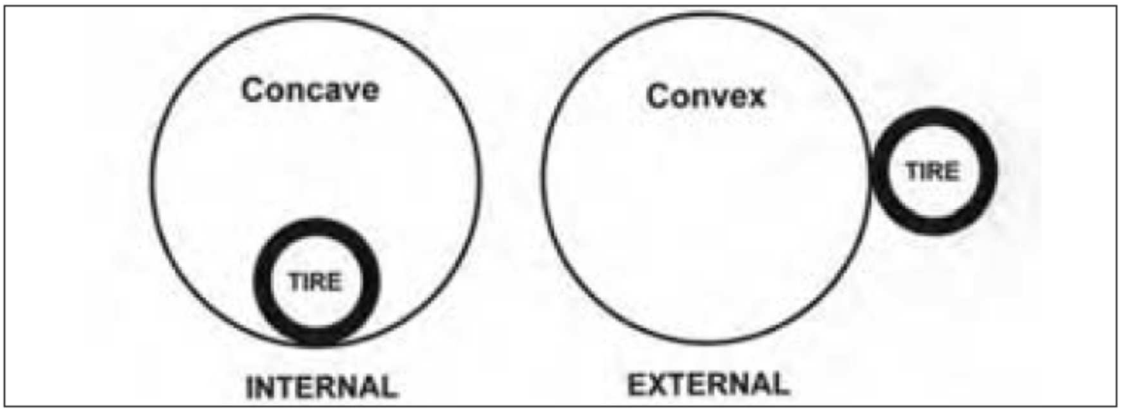

Figure 7. Concave and convex roller drum tyre testing apparatus configurations from (Gent and Walter 2005)

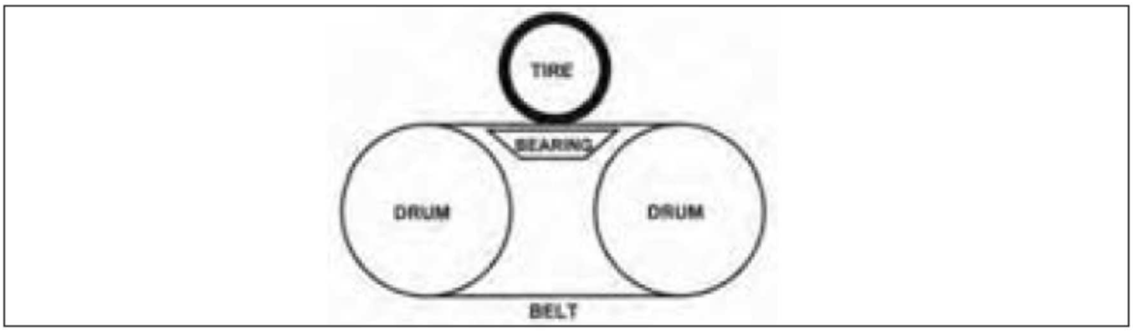

Figure 8. Flatbed belt tyre testing apparatus from (Gent and Walter 2005)

In the on-road situation the tyre clearly operates on a flat surface and thus the contact patch vertical force distribution on the roller drum machines differs from that experienced by the tyre on the road. The pattern of the normal force distribution in the contact patch is affected by the radius of the drum – the larger the radius the more closely the drum approximates a flat surface.

The flatbed machines generate a more realistic contact patch but have some other disadvantages. The moving plank type of machines can only operate at very low speeds while the belt type machines are very expensive particularly if they are required to handle the loads associated with heavy truck tyres.

Generally the flatbed machines return higher values of cornering stiffness than the roller drum machines. To assist the NHVR, the Australian Tyre Industry Council (ATIC) commissioned the testing of eight tyres on the flat bed testing machine at the Smithers Rapra facility in the USA. For one these tyres they have also provided us with the data from roller drum testing by the manufacturer of the same tyre. The lateral forces from the roller drum testing were up to 17% lower than from the flatbed testing and the aligning moments were up to 28% lower. Other reports have found the lateral forces from roller drum tests can be 30% or more lower than those from flatbed tests. However, the relationship between the test results from the two types of machine is complex and there is no simple way of converting from one to the other (Gent and Walter 2005).

The "over-the-road" machines are typically a heavy truck or trailer vehicle where the test tyre can be mounted centrally and runs on the road. Varying vertical forces, slip angles and camber angles can be applied and the resulting lateral forces and aligning moments are measured. ARRB have developed one of these facilities which is shown in Figure 9.

"Over-the-road" test machines provide the most realistic simulation of the actual in-service tyre behaviour but it is more difficult than in the laboratory to control the test conditions. Thus, generally the accuracy and repeatability of the test results from "over-the-road" machines is not as good as that from laboratory machines. This is reflected in the SAE recommended practice where the ideal system tolerances for measurement accuracy for "over-the-road" machines are substantial larger than those for laboratory machines.

Figure 9. ARRB "over-the-road" tyre testing machine.

Tyre Classification Schemes

When a PBS assessor undertakes an assessment of a vehicle design, the computer modelling system will require him or her to enter data for the properties of the tyres that the vehicle is fitted with. This data would usually be obtained from the tyre suppliers. If the assessment shows that the vehicle's performance is satisfactory, a PBS permit application will be submitted to NHVR and this application will show the make and model of the tyres used in the assessment. If the application is successful the resulting permit is then only valid for those specific tyres.

Clearly there are a number of practical difficulties associated with this approach. Models of tyres become obsolete. The tyre manufacturer will, of course, replace the obsolete tyre with a new model but this will probably not have identical cornering stiffness and aligning moment properties to the tyre it replaces. Tyres are a consumable item and are replaced regularly during the life of the vehicle. Australia is a large country and much of it is quite distant from the major population centres. Thus, when a tyre fails in a remote area it may not be possible to replace it with the specified make and model of tyre within a reasonable timeframe. Even without the urgency of a tyre failure, an operator may wish to change tyre supplier for business or other reasons. Any change of tyres from those specified on the permit invalidates the permit and thus, in principle, the operator is required to have the vehicle reassessed with the data for the alternative tyres and apply for a variation to the permit.

To try to overcome these difficulties, two of the PBS assessors have been developing tyre classification schemes which enable similar tyres to be grouped together. Thus a PBS assessment based on one of these tyre classes would apply to all tyres in that class.

The tyre classification scheme developed by Tiger Spider has six categories (Coleman 2018). Each of these categories is represented by a virtual reference tyre with defined lateral force versus slip angle curves at various vertical loads. These curves are based on real tyre data. The magnitude of the curves has been scaled to generate a spread of tyre performance between the categories. As far as I am aware, the details of how the curve fitting and scaling were done have not been published are proprietary intellectual property belonging to Tiger Spider. The categories are hierarchical with category 1 being the best performing tyres and category 6 being the worst performing. In principle, category 6 represents the worst-performing tyres available in the market. Thus, if a vehicle passes the PBS requirements with the category 6 virtual tyre it should have satisfactory performance with any tyre. The hierarchical nature of the scheme means that, for example, if a vehicle requires category 3 tyres to achieve satisfactory performance, it would be able to use any tyres from categories 1-3 but not tyres from categories 4-6.

Actual tyres are allocated to categories based on their measured data characteristics. It is not entirely clear how this is done. (Coleman 2018) states that it is done conservatively with a safety factor so that there is some certainty that the "real" tyre will outperform the "virtual" tyre representing its category. This illustrated (Coleman 2018) by applying the "real" tyre data for 165 tyres to three reference vehicles and comparing the HSTO results to those of the "virtual" tyres.

An alternative classification scheme has been developed by Mechanical System Dynamics (MSD). This uses the similarity method developed by Pacejka, which is widely known as the Magic Formula. Using the tyre cornering stiffness data presented by (Domprobst 2016) and a process of linear interpolation and extrapolation, MSD created a set of 25 curves spanning a range from low cornering stiffness to high cornering stiffness numbered from 1 to 25. They then identified that the range of curvature in the tyre test data that they had was far greater than shown in the Domprobst curves and so they created six families of curves based on scaling the data set. The original data set was designated as group B and thus there was one group of higher stiffness (group A) and four groups of lower stiffness (groups C to F). The result is a matrix of tyre stiffness characteristics with six rows (A-F) and 25 columns (1-25) giving a total of 150 virtual tyres. This classification system has been implemented in spreadsheet form and with the tyre data tested so has been shown to be able to provide a close match to the measured data of the cornering stiffness versus vertical load relationship. The Magic Formula is then used to generate the cornering force versus slip angle curves.

Within each group, the virtual tyres are in order of increasing cornering stiffness, i.e. tyre B12 has higher cornering stiffness than tyre B11. Similarly across groups, tyre B12 has higher cornering stiffness than tyre C12. However, MSD have some reservations about applying a hierarchy to the tyres for PBS purposes. That is, if vehicle achieves all the PBS requirements with a B12 tyre, they do not guarantee that it will pass with all Bx tyres where x is larger than 12. Specifically they have suggested that in some cases, a tyre with higher cornering stiffness will improve HSTO but worsen RA. Thus is a vehicle is close to the pass/fail limits for both measures using a tyre with greater cornering stiffness may cause it to fail RA.

The MSD classification system has not yet been applied to the same extensive range of tyre data as the Tiger Spider system. However, with 150 categories it is quite likely that when this is done there will be a large number of categories with no tyres, a significant number of categories with only a small number of tyres (1-2) and a small number of categories with a larger number of tyres (perhaps 5-10).

DISCUSSION

When the PBS system was developed there was a process to determine the pass/fail criteria for each of the performance standards at each access level. Wherever possible, the pass/fail criteria were based on a quantifiable relationship between the performance measure and safety risk. However, for many of the performance measures no quantifiable relationship was known. In the situation, the pass/fail criteria were based on the performance characteristics of the current fleet (at the time). Generally the level of the PBS standards were set to generate better performance than the worst performing vehicles in the fleet. The rationale for this is simple. Current vehicles are accepted by the public as having adequate safety and PBS vehicles should represent a safety gain.

The performance characteristics of the fleet were determined by computer simulation on a large number of vehicle configurations (Prem, de Pont et al. 2002). The tyre data used in these simulations was the published data for the Michelin XZA tyres which had been tested using the UMTRI test trailer. Thus the reference values for many of the performance standards are based on a specific tyre. (Coleman 2018) states that the Tiger Spider category 1 virtual tyre essentially matches the performance of this Michelin XZA tyre, i.e. it is equivalent to the best performing tyres in the Tiger Spider classification scheme. However, when we compare it to the eight tyres that ATIC sent to Smithers Rapra for testing we see that it is roughly mid-range in performance. Nevertheless what this means is that the fleet vehicles were modelled with tyres that are in the mid to upper range of cornering stiffness rather than with the full range of tyre performance that was in use.

The most popular PBS vehicles are truck and dog trailer combinations followed by A-doubles. These vehicles have very good low speed turning performance for their length but there is a trade-off between low speed turning performance and high speed dynamic performance and thus for these configurations high speed transient off-tracking (HSTO) and rearward amplification (RA) are often the critical standards in the PBS system.

The cornering stiffness data used in the computer simulations has a significant influence on the HSTO and RA results and this can often mean the difference between satisfactory and unsatisfactory performance under the PBS system requirements. Cornering stiffness data for a given tyre is obtained by using some form of test apparatus. Although, with properly conducted tests, the results for a given test facility are repeatable and consistent, there are substantial differences between the results for the same tyre from different test facilities. Furthermore, differences in the way that the tests are conducted can also influence the results significantly. For example, it is known that the cornering stiffness increases as the tyre becomes more worn and thus removing some of the tread by buffing the tyre will result in tyre data that shows a significantly higher level of cornering stiffness than would be the case if a standard new tyre had been tested.

PBS assessors generally rely on tyre data provided to them by the tyre manufacturers or suppliers. Although all the major tyre manufacturers will have testing equipment that can use to measure cornering force vs vertical load and slip angle as required, the purpose of this equipment is primarily for research and development and quality assurance. For them it is more important that the results are consistent and repeatable and not so important that they accurately represent the on-road performance of the tyre in detail. Most tyre manufacturers use roller drum machines which are known to report lower levels of cornering stiffness than flatbed machines. For comparing the performance characteristics of tyre A with tyre B this is not an issue but when providing data for use in PBS assessments this can be important.

The SAE has developed a recommended practice document providing detailed guidelines for how cornering tests on truck and bus tyres should be undertaken. However, there is no requirement for the providers of tyre test data in Australia to comply with this recommended practice. Furthermore, the SAE document recognises the issue of differences in the results from different types of test apparatus.

There are allegations that some of the tyre data that has been provided to assessors is of dubious quality in that it has been obtained from tyres that have had a significant proportion of their tread removed by buffing or simply that it is fraudulent. To try to overcome this, the ATIC has proposed that a centralised database of tyre data should be established which they would administer. The concept of a single database of tyre properties that all PBS assessors would use has considerable merit. However, there are some issues with the details of the ATIC proposal:

- The first is that inclusion in the database is only open to ATIC members. As noted on their position paper ATIC members import 70-80% of the truck tyres used in Australia. Thus 20-30% of the truck tyres used in Australia are not covered by this proposal
- Secondly the proposal specifies that the tyre testing will be carried out at relatively low speeds on a roller drum machine. Generally flatbed machines measure high levels of cornering stiffness than roller drum machines and cornering stiffness increases with test speed. Thus the testing approach will probably underestimate the cornering stiffness of the tyres.
- It has been alleged that some tyre suppliers have been providing assessors with tyre data of dubious quality and/or provenance. The proposal states that suppliers will be able to upload the data for their products. It is not what safeguards will be put in place to ensure the integrity of this data.
- The make and model of the tyres will be hidden from the assessors. It is not clear how this can work. Generally the assessors do not choose the vehicle's tyres. If an assessor is presented with a vehicle design where the operator wishes to use brand x, model y tyres, how does he or she obtain the data for those tyres? Conversely, if an assessor submits a PBS application with a coded anonymous tyre identifier and the permit is subsequently issued specifying that the tyres should be brand x, model y, then the assessor will then be able to match the tyre to its properties.
- Finally the assessors will still be required to assess each tyre option for the vehicle if they wish to give their clients a wide range of choice. The paper on the Tiger Spider classification system shows data for 165 tyres. The cost of evaluating a wide range of tyre options is potentially still very large.

The ATIC proposal does identify and try to address one of key issues. It is highly desirable that all assessors should have access to and should be using the same data for the same tyres. The integrity of the PBS system is undermined if a vehicle fails to achieve the requirements with one assessor and then passes with another assessor. At the margins this will occur anyway because of differences in the modelling systems and particularly the driver model but as much as possible this problem should be avoided.

One of the most important issues for operators is the ability to use a range of tyres on their vehicles rather than being limited to the specific make and model of tyre used in the PBS assessment. This issue is also important to tyre suppliers because it limits their ability to compete for customers. This problem is compounded by the lack of consistency in the tyre data from different test machines. For example, a tyre manufacturer may be able show that his product is functionally equivalent to a competitor's product by testing both tyres at his test facility and showing that they have substantially the same cornering stiffness and aligning moment characteristics. However, the manufacturer's "official" test data for the competitor's product may come from a different type of test facility and show substantially different cornering stiffness characteristics. In some cases this will mean that, using the "official" manufacturer data, a vehicle passes the PBS requirements with one the tyres and fail with the other even though the two tyres are substantially the same.

A potential solution to this is to require PBS tyres to all be tested on the same machine or, at least, the same type of machine. ARRB has developed an "over-the-road" testing machine that could be used for this task. The testing cost for this machine are $2,500 + GST per tyre provided the testing is done is batches of six tyres or more. This is relatively modest cost given the price of tyres and the numbers sold in Australia. Not all tyres would necessarily need to be tested. The scheme could operate like the "road-friendly" suspension requirements where tyres would need to be tested to achieve a superior performance rating while untested tyres would be deemed to have a standard level of performance. There may be concerns about establishing a monopoly situation for the testing agency. This could be mitigated by specifying the testing requirements rather than the testing facility but, given the size of the market, it is unlikely that a competitor would establish themselves in Australia. Other international testing facilities could compete.

Although PBS assessors can provide a list of suitable tyres on the PBS application, this requires them to evaluate the vehicle's performance with each of these tyres. If the vehicle has good performance for the PBS standards that are sensitive to tyre properties, this can potentially be done without undertaking a computer simulation for each tyre model. However, if the critical PBS standards for the vehicle are those that are sensitive to tyre properties, it may be necessary to run the computer simulation for each tyre option. In this case, providing the operator with a list of suitable tyres involves substantial additional work and hence cost.

Tyre properties have the most effect on the performance measures associated with the high speed lane change manoeuvre, namely HSTO and RA. These two performance measures are often the critical ones for truck and dog trailer combinations and for A-doubles. Currently truck and dog trailer combinations make up 55% of approved PBS vehicles and A-doubles represent a further 10%. Thus for a large proportion of the PBS fleet, tyre properties are important in determining whether or not the vehicle meets the PBS requirements.

To overcome the issue of how to provide a list of tyre options for operators two PBS assessors have developed classification schemes. In the first instance, these schemes group tyres together with other similar tyres and create a representative set of tyre properties for the group. A PBS assessment can then be undertaken using the representative properties for the group and the outcome would apply to all tyres in the group. The two schemes differ somewhat in their approach.

The Tiger Spider scheme has six categories and the allocation of tyres to categories is said to be conservative although the details of how this is done have not been provided. The categories are also hierarchical so that if, for example, a PBS assessment determines that a vehicle will pass with category 3 tyres then it can be fitted with any of the tyres in categories 1, 2 or 3 but not those in categories 4, 5 or 6. The details of the scheme are proprietary to Tiger Spider and thus currently cannot be used by other PBS assessors. Furthermore, it is not clear how NHVR can audit PBS assessments undertaken by Tiger Spider using the scheme.

The MSD scheme has a 6 by 25 matrix of categories making a total of 150. As a result each tyre's properties will match the representative properties for its category quite closely. Currently the scheme has only be applied to a relatively small number of tyres and so it not known how many tyres will be in each category when the scheme is applied to the range of tyres available in the market. However, it is not likely to be very large even for the most popular categories. At this time, the scheme has not been shown to be hierarchical although, in my view, it is quite likely to be so.

Both schemes are reliant on tyre data to assign tyres to categories and so the issues associated with consistency of data between testing facilities which were identified above apply equally to the classification schemes.

OPTIONS

In this section we propose a number of alternatives for how to proceed. These are intended to be a basis for discussion and to stimulate stakeholder feedback. The options are not comprehensive and we welcome feedback that suggests alternative approaches. Furthermore, at this time we are making no recommendations in favour of any of the proposals. We will be guided by the stakeholder feedback.

There are two fundamental issues that have identified. One is the quality and consistency of tyre data. The other is the need for flexibility to be able to use a range of tyres on the vehicles. Not every option addresses both these issues in full.

Establish a centralised database of tyre data

This option is a variation of the ATIC proposal. The requirements for tyre testing would be specified. These could be as detailed as those in the SAE Recommended Practice but probably would be a little more flexible. However, they should preclude buffing and techniques to get artificially high cornering stiffness readings. All data in the database should be based on actual testing with details of the testing laboratory, testing equipment and test date recorded. All tyre suppliers should be able to submit data to the database. All PBS assessors should have access to and be required to use the data in the database. This access should include the make and model of the tyres. Assessors could still use their own classification schemes but these must be based on the tyre data in the database. Such classification schemes would have no formal status with NHVR and PBS applications would be required to specify the tyre makes and models that apply. Any audits of these PBS assessments would be based on the actual tyre data not the proprietary classification scheme.

This option goes some way to addressing the issue of data consistency. The sources of the tyre data would be traceable and could be checked if necessary. All assessors would be using identical tyre data which would eliminate one source of variability between assessors. Assessors who have developed classification systems could continue to use them but they would be absolutely responsible for the validity and reliability of their system.

This option does not directly address the issue of enabling operators to use a range of tyres. The assessor would have to determine which tyres could be used by evaluating each one in some way.

There is also the question of who would establish, maintain and fund the database. In the ATIC proposal they offered to do this but this was a database for ATIC members only. In my view, the best solution is for the database to be under NHVR control although the actual work could be contracted out. It could be funded through a fee for each tyre dataset as it is entered or in some other way.

Specify one set of generic tyres for all assessments

This approach effectively eliminates tyres as factor in PBS assessments. Generic tyre data would be generated and used by all PBS assessors. It is likely that there will need to be different sets of data for different tyre sizes but for a given tyre size there would only be one dataset. All assessors would be using the same data which would improve consistency and PBS vehicles would be able to use any tyre of the designated size. Thus the PBS permit would only specify tyre size.

This approach addresses the consistency of the tyre data and the flexibility to use a range of tyres. It lacks somewhat in the area of data quality. The actual performance characteristics of the vehicle during the lane change manoeuvre will differ from the calculated characteristics and in some cases will be worse. However, the pass/fail criteria for those performance standards were based on applying generic tyre data to the fleet so the reference values would also have varied. Nevertheless, there are likely to be some vehicle and tyre combinations that, under the current regime of using "actual" tyre data, would fail to achieve the PBS requirements but would pass when using generic tyre data.

It is worth noting that Tiger Spider (Coleman 2018) state that level 1 truck and dog trailer combinations typically require their category 1 tyre (best performing tyre) to meet the HSTO requirements. For this option we would expect that the performance of the generic tyre would be mid-range and thus it is likely that some current truck and dog combinations would not pass. The geometry of a truck and dog combination also has a significant effect on its performance during the lane change and its performance can be improved through changes to the coupling offset, drawbar length and trailer wheelbase. Under this proposal, the inherent performance of these combinations would need to be improved through geometric design and suspension selection rather than relying on the tyres.

Some costs will be involved in creating the generic datasets but beyond that this is a low cost option.

Non-hierarchical classification system

The MSD classification system in its current state is non-hierarchical. That is, if a PBS assessment of a vehicles uses the virtual tyre data associated with one of the categories and meets the requirements, there is no automatic assumption that it will also pass with other categories that have higher cornering stiffness. Assessors may, however, be able to infer a range of categories that would work by evaluating a selection of categories rather than all of them.

The current MSD system has six families of cornering stiffness characteristics with 25 members in each family giving a total of 150 categories. By having this large number of categories, they are able to match any set of actual tyre data to one of the categories with a relatively good quality of fit. Note that, at present, this has only been tested with about 15 sets of tyre data. With 150 categories, it is likely that even the most popular category will contain a relatively small number of tyres. However, it is not essential to have 25 members in each family. The MSD system could span the same range of tyre properties with, say, 10 members in each family which would result in a total of 60 categories. The quality of fit when matching real tyre data to one of the categories would not be as good and so the accuracy of using the virtual tyres to represent actual tyres will be lower but the number of tyres in the popular categories will be much larger.

Under this system, the PBS assessors would have access to the data for a set of virtual tyres representing each of the categories and a table showing which real tyres are included in each category. Thus a PBS assessment based on a specific virtual tyre would automatically allow the operator to use any of the tyres in that category. For this to work well we would require a centralised database of tyre properties as described in option 1 but the PBS assessors would not need to have access to this database. Without the centralised database this option would still be subject to the problems of data consistency and reliability that we currently have. The allocation of actual tyres to categories would be done by the database manager. MSD has developed spreadsheet software for their classification system which can be used to classify tyres and to generate virtual tyre data. If the MSD system were to be adopted this could potentially be used but this would need to be negotiated with MSD.

This approach would result in all PBS assessors using the same sets of tyre data which should enhance the consistency of assessments by different assessors. An assessment based on the more populated tyre categories would provide the operator with a list on acceptable tyres for the vehicle. However, this list may vary from vehicle to vehicle and so there may be management issues associated with keeping track of what tyres are acceptable on each vehicle.

Some better-performing tyres may be disadvantaged by this approach if they are the only tyre (or one of only two or three) in their category. Assessors will probably aim to provide their clients with the largest possible list of suitable tyres for the least amount of effort. Thus they will choose evaluate the vehicle with tyre categories that include a large number of tyres and not bother with categories that have very few tyres.

Hierarchical classification system

The Tiger Spider classification scheme is hierarchical with six categories each with a set of virtual tyre properties. These categories are numbered from one to six with one being the best performing tyres and six being the worst-performing. The hierarchical nature of this scheme means that if a vehicle is assessed with the virtual tyre associated with one of the categories and is deemed satisfactory, it will be able to use any of the tyres from that category or any of the tyres from all of the higher performing categories. To make this work, the allocation of tyres to categories has to be done conservatively but this approach facilitates the use of a relatively large number of tyres with any given assessment.

The details of how the Tiger Spider classification system works have not been published and so we do not know how the virtual tyre properties were generated nor how the data of real tyres is used to allocate these tyres to the categories in a conservative way. It appears that this may be done by simulating several reference vehicles with the real tyre data and comparing the results with those from the same vehicles fitted with the virtual tyres representing each of the categories but this has not been explicitly stated in the published descriptions. In my view, the NHVR would need to know in detail how the system works before they could adopt this as the approved method.

Although the MSD classification method is not currently hierarchical, it could be made so. This would require so R&D to ensure that the allocation of tyres to categories is done conservatively and to verify that "superior" cornering stiffness always generates superior performance.

As with the previous option, this option will work best if there is a centralised database of tyre properties as outlined in option 1. Again, the assessors will not need to have access to this database as their assessments will be based on the virtual tyres associated with each of the tyre categories.

The hierarchical approach should overcome the issue raised in the previous option where a better-performing that is in a category of its own might not be considered by the assessors. If the vehicle passes with lesser-performing tyres, it will automatically be able to also use the superior tyres. Because the allocation of tyres to categories must necessarily be conservative, there will be instances where a vehicle would pass if the actual tyre data is used but do not pass when the virtual tyre data for the tyre's category is used instead.

As noted, the Tiger Spider classification scheme already exists and potentially NHVR could negotiate an arrangement to make this scheme available to all assessors. However, the specifics of how the scheme works should be then open to scrutiny and peer review. Alternatively the MSD scheme could be further developed to be hierarchical. Again the rights to use the scheme would need to be negotiated with MSD.

Obviously it would also be possible to independently develop a similar scheme and thus avoid negotiations with the developers of the existing schemes. However, this would take longer and would probably be more costly.

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