MANAGING TYRE MODELLING IN A PBS SYSTEM

LASZLO (LES) BRUZSA
Chief Engineer – Productivity & Safety
National Heavy Vehicle Regulator, Australia
www.nhvr.gov.au
les.bruzsa@nhvr.gov.au

JOHN DE PONT
Director of Engineering Research at TERNZ.
Obtained BSc, BE (hons) and ME from University of Auckland and PhD from Cambridge University.

Abstract

Since the inception of the Australian PBS system, tyres have been treated as a vehicle parameter in a similar way to suspensions. Thus, when a PBS assessment is undertaken, it is dependent on the tyre properties and the application for a design approval will specify the tyres on which the assessment was based.

However, there are some characteristics of tyres that are different from those of other vehicle parameters which complicates this approach. Tyres are a consumable item and, over the life of the vehicle, all the tyres will be replaced quite a few times. Furthermore, any tyres of the same size will fit as replacements. Two of the key tyre properties for PBS assessments, cornering force and aligning moment, are both non-linearly dependent on vertical load and slip angle. This makes it difficult to directly compare the characteristics of different tyres and, particularly, to determine whether alternative tyres will improve or worsen the vehicle's performance. The issue of the key tyre properties is further complicated by the fact that different tyre testing facilities can produce significantly different results for these properties when testing the same tyre.

These factors cause a range of issues for the various stakeholders in the PBS scheme relating to consistency, compliance, and costs. Thus, the National Heavy Vehicle Regulator commissioned a review to find an approach for managing tyres within the PBS scheme that was acceptable to the majority of stakeholders.

Keywords: Performance Based Standards, Vehicle dynamics modelling, Tyre properties Transport, Symposium

1. What is the issue?

Since the inception of the Australian PBS system, tyres have been treated as a vehicle parameter in a similar way to suspensions. Thus, when a PBS assessment is undertaken, the results are dependent on the tyre properties used in the analysis and the application for a design approval will specify the tyres on which the assessment was based. However, there are some characteristics of tyres that are different from those of other vehicle parameters, which complicates this approach.

Firstly, tyres are a consumable item and, over the life of the vehicle, all the tyres will be replaced several times. Furthermore, any tyres of the same size will fit as replacements. Secondly, two of the key tyre properties for PBS assessments, cornering force and aligning moment, are both non-linearly dependent on vertical load and slip angle. This makes it difficult to directly compare the characteristics of different tyres and, particularly, to easily determine whether alternative tyres will improve or worsen the vehicle's performance. The issue of the key tyre properties is further complicated by the fact that different tyre testing facilities can produce significantly different results for these properties when testing the same tyre. Although these differences may be due in part to differences in the testing procedures used, which can be addressed by tightly specifying the testing requirements, they are also due to inherent differences in the testing machines, which is a more challenging issue.

Cornering force and aligning moment have a significant impact on high-speed dynamic performance, particularly High-Speed Transient Off-tracking (HSTO) and Rearward Amplification (RA). These two performance standards are often the critical ones for truck and full trailer combinations and for A-doubles, which are the two most popular configurations operating under the Australian PBS system.

Tyre characteristics cause a range of issues for various stakeholders in the PBS system. To be able to supply tyres for PBS vehicles, tyre distributors need to provide tyre cornering force and aligning moment data to the PBS assessors. This data is not routinely measured by tyre manufacturers and is not published. The larger tyre manufacturers do have the facilities for measuring these tyre properties and so the distributors of these tyre brands can commission tests from the manufacturer. Other tyre distributors have to commission tests from independent testing laboratories. As noted above, tyre testing results are not necessarily consistent between test facilities which results in a lack of confidence in the credibility of some of the test data. Furthermore, tyre manufacturers are continuously developing and improving their products. Whenever a model of tyre is superseded by new model, the new model needs to be tested because the tyre characteristics may have changed.

PBS assessors will typically assess the vehicle design using the tyre data for the make, model and size of tyre specified by the vehicle designer. If the vehicle fails to achieve the PBS requirements for high-speed dynamic performance, the assessor may suggest using different make and model tyres which produce better performance. The assessor may also evaluate the performance with several different tyre options so that the operator has a choice. Two of the assessors have each developed a classification scheme for tyres so that they can evaluate the vehicle with representative tyre data and then submit the PBS application with a list of allowable tyre options covered by the representative data. One of the issues with this approach is that these classification schemes are proprietary and thus not available to other assessors.

For operators problems arise because, for many of their vehicles, the PBS design approval will be based on specific makes and models of tyres. When these tyres need replacement, they must be replaced with one of the tyre options listed on the design approval or the vehicle will no longer meet the requirements of its PBS approval. However, at times it may be impracticable to use the approved tyres. For example, a tyre may fail in a remote area where the specific make and model of tyre is not readily available, or the tyre model may be superseded by a new model. In other cases, an operator may wish to change to a new tyre supplier with different brands for commercial reasons. Any change from the tyres listed on the design approval requires the operator to get another PBS assessment done based on the new tyres.

Finally, PBS certifiers and enforcement agencies need to verify that the vehicle is fitted with the tyres listed on the design approval. If this list is extensive this can be a cumbersome task.

2. What did we do?

The process of reviewing tyre management practice in the PBS system was undertaken as follows:

- A discussion paper was prepared outlining all the issues relating to tyres in the PBS systems that the author was aware of and outlining some possible options to resolve them.
- The discussion paper was circulated to key stakeholders in the PBS system with a request for feedback. To facilitate the analysis of the feedback, a template form was provided. The discussion paper was also published on the NHVR website with an open invitation to provide feedback.
- There were 24 feedback responses to the discussion paper. This feedback was summarised and then presented at a one-day stakeholder workshop which was held in Melbourne on May 2019.
- The feedback from the workshop was not completely consistent with written feedback to the discussion paper and a further one-day workshop for PBS assessors was organised by the NHVR to develop a consensus position for that stakeholder group.
- A draft final report was prepared and circulated.
- A further workshop was held in Sydney in January 2020 where the recommendations of the final report were presented together with the proposed approach developed by the PBS assessors.
- Based on the recommendations in the final report, the NHVR engaged ARRB to undertake some further tyre testing to clarify some of the issues raised.
- The NHVR also commissioned the five main PBS assessor organisations to reassess ten PBS vehicles, which they had previously assessed, and which had been approved, using the recommended generic tyre data approach.
- The first stages in implementing the recommended generic tyre data approach have also now been completed.

3. What did we find?

One of the biggest challenges is obtaining consistent and accurate tyre data. For consistency, the data should be substantially the same regardless of which test facility undertook the measurements and should exhibit good repeatability. By accurate we mean that the tyre data should accurately match the on-road response of the tyres when fitted to a vehicle.

When the PBS system first came into operation, most, if not all, of the tyre data was provided by the tyre suppliers. Most of the large name-brand tyre companies have in-house testing facilities and the suppliers of these tyres could commission the manufacturer to undertake the testing. Other tyre suppliers commissioned tests from independent testing providers. Each testing facility uses its own protocols and thus there was no real consistency in the data between test facilities. More recently many tyres have been tested by the ARRB tyre testing trailer. This is an over-the-road facility and thus the data should be more representative of on-vehicle performance, i.e., more accurate. With the same protocol and equipment being used for every test, a greater degree of consistency is claimed, although, with over-the-road testing, it is much more difficult to control the test conditions and thus the measurement precision is less.

The ARRB tyre test trailer was developed for a project to measure the pavement wear generated by horizontal tyre forces (Ai, Sharp et al. 2017). The measurement results in this report show the lateral forces for different slip angles at a constant vertical load. These measurements showed quite large variations in lateral force for repeat runs with varying slip angles at the same test site as shown in Figure 1, which is reproduced from Ai, Sharp et al. (2017). This illustrates the lack of precision in these measurements. More significantly there were also large variations (22%-29%) in the average horizontal force for a given slip angle at different sites as shown in Figure 2. This indicates that the road surface at the test site also has a significant effect on the cornering force, i.e., the cornering force properties of the tyre are due to both the tyre properties and the road surface properties.

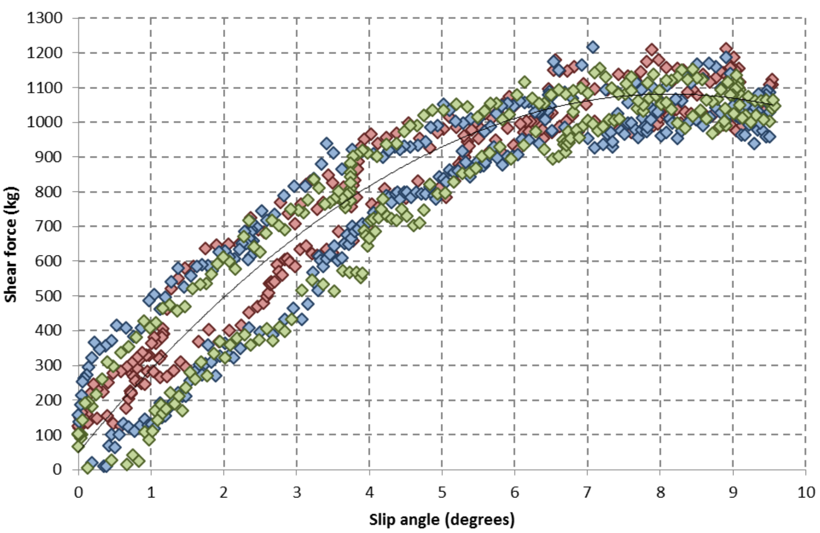

Figure 1. Shear force as slip angle is varied for three runs (different colours) at one vertical loading level.

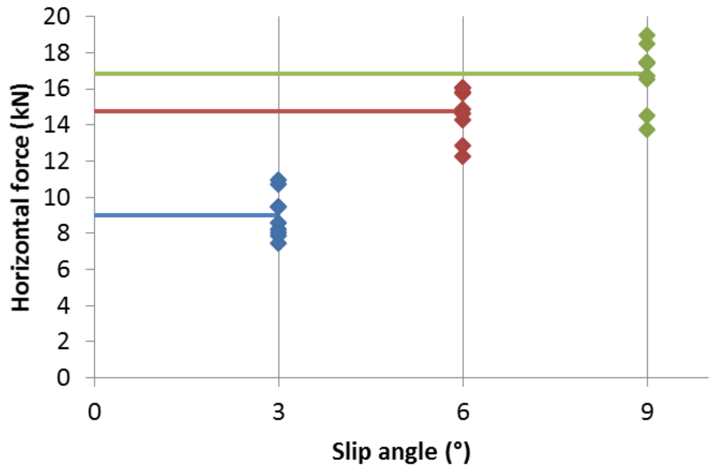

Figure 2. Horizontal forces applied to seals across 24 test plots (reproduced from Ai, Sharp et al. (2017)).

Laboratory-based testing from a single laboratory should produce consistent tyre data but this is not necessarily an accurate representation of the tyre's behaviour on a vehicle on a road. There is variability in the data from different test laboratories. We had a report from Volvo (Fröjd 2018) where they had sent a single tyre to four different test facilities belonging to premium brand tyre suppliers. Volvo specified a minimum test speed of 30 km/h, a regulated inflation pressure, vertical load and slip angles. However, they did not specify the type of test machine or the breaking in and warm up procedures. After the four tests were done, the tyre was sent back to the first test facility for re-testing. This re-test showed very good repeatability so there was no wear-related change in tyre properties. Nevertheless, there was a difference in cornering stiffness of up to 30% between the different test facilities. This variability could possibly be reduced by tightly specifying the testing protocols. Over-the-road testing facilities are inherently less consistent because it is more difficult to control the test conditions. The resulting data are more representative of the on-vehicle behaviour of the tyre but can vary significantly between test sites.

In the discussion document that we circulated to stakeholders we suggested four possible options. These were:

1. Establish a centralised database of tyre data.
2. Specify one set of generic tyre data for all assessments.
3. Non-hierarchical classification system.
4. Hierarchical classification system.

The centralized database would resolve the issue of ensuring consistency of tyre data between assessors but does not address the issue of consistency between test facilities or accuracy. It also does not resolve the problems for operators of having their PBS approval based on specific makes and models of tyres.

The generic tyre data approach standardizes the tyre data used by all assessors. The tyre data would need to be scaled for different tyre sizes, but the PBS approvals would simply specify the tyre sizes on which the approval is based. Operators would then be free to use any tyres of the approved size and load rating. A criticism of this approach is that it does not consider the differences in performance characteristics of different makes and models of tyre.

The two classification systems were based on the systems that had been developed by two of the PBS assessors. The hierarchical system was developed by Tiger Spider and has been described at a previous HVTT symposium (Coleman 2018). This system has six categories with each category represented by a virtual reference tyre data set. It appears that real tyres are assigned to a category based on how they perform on some reference vehicle models. The details of how this classification process works have not been published. The categories are hierarchical with category 1 being the best performing tyres and category 6 being the worst performing tyres. The hierarchical nature of this classification scheme means that if, for example, a vehicle requires category 3 tyres to achieve satisfactory performance, then it can be fitted with any tyres from categories 1-3, but it cannot use tyres from categories 4-6.

The other classification scheme was developed by Mechanical System Dynamics and is based on matching the measured tyre cornering stiffness data to the nearest virtual reference tyre. This classification system has a matrix of 150 virtual tyres – there are six stiffness categories, labelled A-F, with 25 virtual tyres, numbered 1-25, in each. This classification system is not designed to be hierarchical and thus, for example, if a vehicle achieves satisfactory performance with, say, a C11 tyre, this does not necessarily mean that it will also achieve satisfactory performance with C12-C25 tyres, or with A and B category tyres, all of which have higher cornering stiffness than the C11 tyre.

The centralized tyre database and both classification system approaches depend on having consistent and accurate tyre data to be effective. If there is a significant level of uncertainty regarding the accuracy and precision of the tyre data, then classifying the tyres into narrow bands of performance is not meaningful because the uncertainty in the data is greater than the difference between the categories.

4. What did we recommend and what have we done?

We recommended the use of generic tyre data. With this approach the tyre data becomes a test condition rather than a vehicle parameter. The question then arises as to what the generic tyre data should be. In our view the most logical choice is to base it on the Michelin XZA data that was used for the development of the Australian PBS system. By using the Michelin XZA data, we are referencing the performance of the current PBS designs back to the performance of the Australia heavy vehicle fleet as assessed in 2001 (Prem, de Pont et al. 2002). As the pass/fail criteria for several of the PBS standards were developed by referencing the performance of the conventional heavy vehicle fleet, this comparison is consistent with the original design of the PBS system. The pass/fail criteria were generally selected so that the performance of PBS vehicles would be superior to that of the worst-performing standard vehicles.

The Michelin XZA data for cornering force was originally presented as an array of 15 values (three vertical loads by five slip angle values). The various simulation packages interpolate this data in some way to find the cornering force for other vertical load and slip angle values. To minimise the variability due to different interpolation methods, we recommended fitting the Pacejka Magic Formula (Pacejka and Bakker 1991) to the data and then evaluating the cornering force with a finer mesh. We recommend a 10x10 array with slip angles from 1 to 10 degrees in one-degree increments and vertical loads of 20% to 200% of the rated load in

20% increments. The Pacejka Magic Formula coefficients used to generate this data should also be published. Assessors could then use the version of the data that best suits their simulation package.

The Michelin XZA-based data would be used for 11R22.5 tyres with a rated load of 2800kg for a single tyre. To accommodate other tyre sizes, we recommend scaling the generic tyre data based on the rated load for tyre. Both the vertical load data and the horizontal force data should be scaled. This would mean that the normalised cornering stiffness coefficient is unchanged. The rated load for a given tyre size depends on the load rating of the tyre and can also vary a little between manufacturers. The NHVR should specify a nominal rated load for each tyre size which applies to all brands. The purpose of this is to avoid a situation where design approvals are based on a specific make and model of tyre. Design approvals should only be based on specifying tyre size. Potentially, the tyre specification could also include the load rating but, if possible, this should be avoided as it adds a level of complication for operators and enforcement officers.

The vertical stiffness reported for the Michelin XZA tyres in the RTAC study (Ervin and Guy 1986) was 788 N/mm. The reported values in the UMTRI Factbook (Fancher, Ervin et al. 1986) show that this stiffness increases as the tyres wear. We therefore propose a generic value of 800N/mm for the vertical tyre stiffness of tyres with a nominal rated load of 2800kg. As with the cornering stiffness data we propose that the vertical stiffness value for other tyre sizes should be scaled in proportion to the nominal rated load. Comparing different tyre sizes in the Michelin catalogue we see that the difference between the rolling radius and half the diameter (i.e., the deflection under the rated load) does not vary much between different tyre sizes which implies that the stiffness is proportional to the rated load.

Work on implementing these recommendations is progressing. The 1991 Magic Formula model (Pacejka and Bakker 1991) has been fitted to the Michelin XZA data. To cover the range of possible manoeuvres we need the tyre data to span vertical loads from zero up to double the rated load. This is because the tyres can be loaded up to their rated load and at the onset of a rollover all the load will have transferred onto one side of the vehicle so the tyres on that side will be at double their normal load. The highest vertical load value in the Michelin XZA tyre data is just over 1.5 times its rated load. If we create a least squares best fit Magic Formula model to this data, we find that, for the higher vertical loads, the lateral model does not behave as expected. To address this issue, we artificially created lateral force data for a vertical load value of double the rated load by extrapolation. Fitting the Magic Formula model to this augmented dataset resulted in a model that fits the measured data well and is also well-behaved for higher vertical loads. Figure 3 shows a comparison of the Magic Formula model with the measured data for lateral force vs slip angle at the different vertical load values. As can be seen, the match is excellent. For the higher vertical loads, it is nearly perfect. For the aligning moment data, the best fit, Magic Formula model was well-behaved at higher vertical loads, and it was not necessary to artificially extend the dataset. A comparison of the Magic Formula model with the measured data is shown in Figure 4.

The Magic Formula models can then be used to provide tabulated data at a much finer mesh than the original measured data. This is illustrated in Figure 5 and Figure 6. To be able to scale this data for different tyre sizes, it was normalised by dividing through by the rated load.

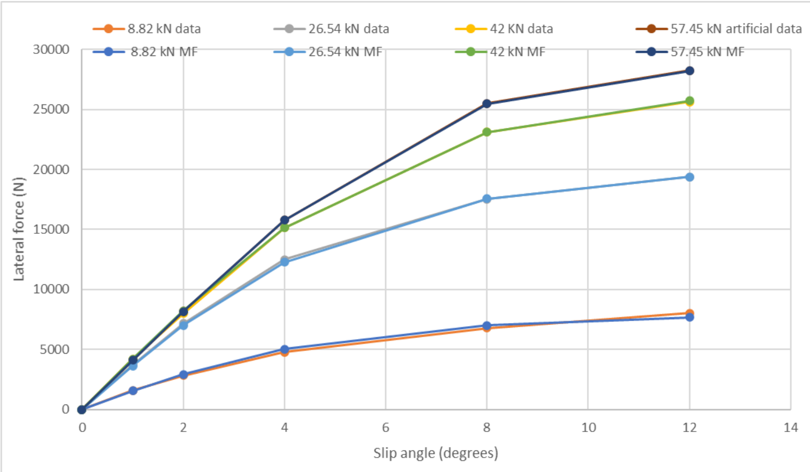

Figure 3. Comparison of Magic Formula with data - lateral force vs slip angle for augmented dataset.

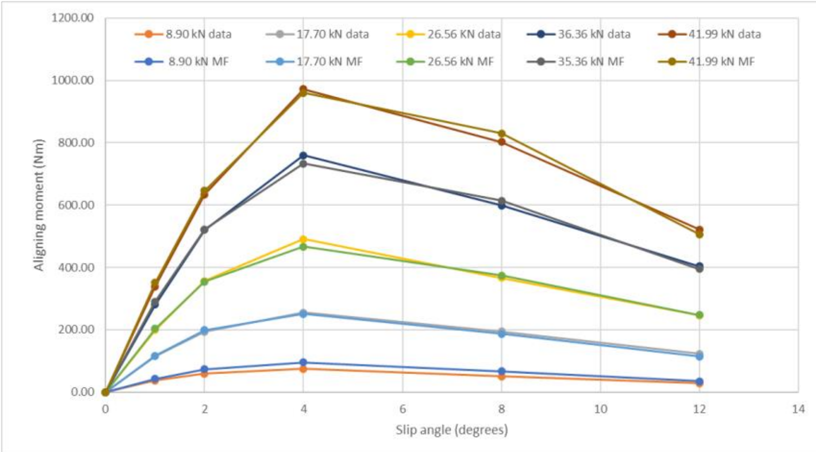

Figure 4. Comparison of Magic Formula with data – aligning moment vs slip angle for five vertical loads.

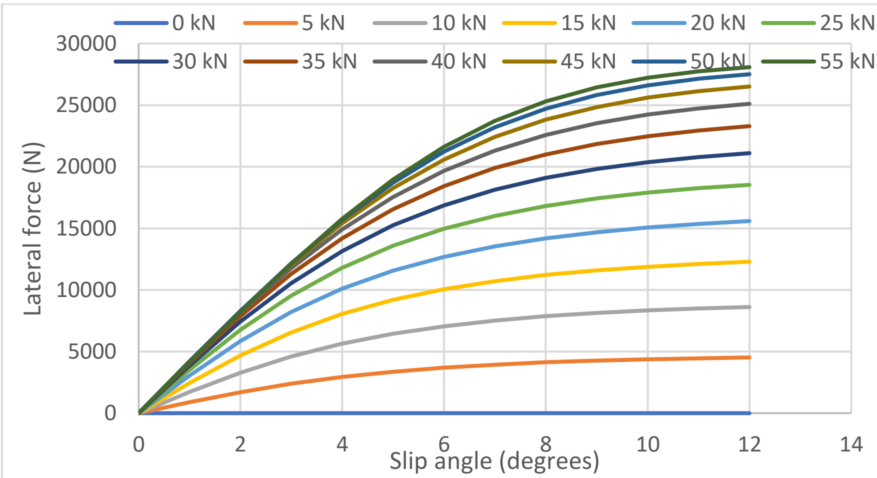

Figure 5. Lateral force data generated from the best fit Magic Formula model using augmented data set.

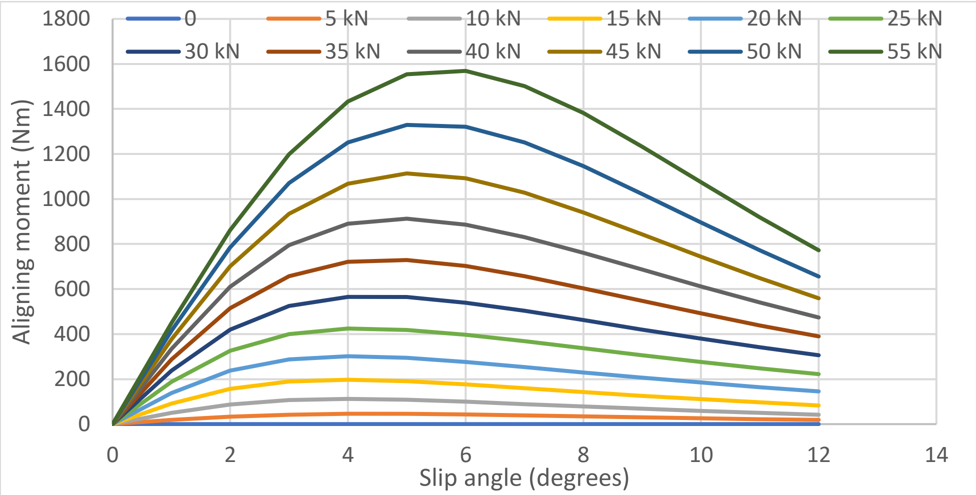

Figure 6. Aligning moment data generated from the best fit Magic Formula model.

To apply this tyre model to different tyre sizes, it was normalised by dividing lateral force, aligning moments and vertical load values by the rated load. This normalised model can then be scaled up to create generic tyre datasets for tyres with different rated loads. Tyres are labelled with a load index which indicates their rated load. The load index values for the heavy vehicle tyres that were tested by ARRB range from 129 to 161 which corresponds to rated loads of 1850kg to 4625kg. Rather than have 32 generic tyre data sets, we have proposed grouping them together in bands spanning five load values and assigning the mid-point rated load to each band. This is illustrated in Table 1. By grouping the load indices in this way most of the common tyres sizes are covered by a single generic tyre dataset. For example, all but one of the approximately 100 11R22.5 tyres tested by ARRB had load indices between 144 and 148 and are thus covered by generic dataset 5. The one exception had a load index value of 143, so to include this the model would need to also be run with generic tyre dataset 4. Similarly all of the R19.5 tyres tested by ARRB would be covered by generic dataset 4. Using this approach, the PBS design application would specify the tyre size and load index range applicable to each axle group.

Table 1. Proposed generic tyre datasets with load index ranges and nominal rated loads.

Generic tyre dataset	Load Indices	Rated Load (kg)	Rated Load(N)
1	128-132	1900	18633
2	132-136	2120	20790
3	136-140	2360	23144
4	140-144	2650	25988
5	144-148	3000	29420
6	148-152	3350	32852
7	152-156	3750	36775
8	156-160	4250	41678

This approach will resolve all of the main issues associated with the management of tyre data within the Australian PBS system. All the PBS assessors would use the same tyre data and so there will be consistency in how tyres are handled within the assessment process. Operators will be free to fit any replacement tyre of the correct size within the allowable load index range. The task for PBS certifiers and enforcement agencies in determining that the vehicle is fitted with the correct tyres will be greatly simplified.

There is still criticism from some quarters that this approach will allow underperforming tyres to be fitted to PBS vehicles and that this will compromise safety. However, the variability in the tyre testing data means that we don't really know whether tyres are actually underperforming or not. Furthermore these same tyres are currently fitted to non-PBS vehicles and there is no good evidence of negative safety impacts attibutable to underperforming tyres.

There are also arguments that some PBS vehicle designs which currently require tyres with a high level of cornering stiffness to achieve the PBS standards, will not achieve the PBS requirements with the generic tyre data at full load and hence will have a reduction in productivity. Again the uncertainty in the tyre testing data means that we really don't know if these high cornering stiffness tyres actually do have superior performance to other tyres.

These issues have not yet been resolved and, at the time of writing, the generic tyre data approach for PBS assessment by computer simulation has not been implemented.

5. References

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