COST EFFICIENT TYRE TESTING, MODELLING AND VALIDATION FOR PBS ASSESSMENTS

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Abstract
At inception Performance-Based Standards (PBS) restricted the vehicle to only operate with a set of approved tyres. Assessors and operators raised concerns about the practical implications of restricting PBS vehicles to a specific set of tyres. Industry concerns are addressed by performing all PBS assessments with a generic tyre model. While this approach simplifies the process, it inevitably constrains the vehicle design and limits the potential payload efficiency benefits of PBS. The VDG (Vehicle Dynamics Group) has developed laboratory and field tyre test equipment, referred to as the Static Tyre Test Rig (STTR) and Dynamic Tyre Test Rig (DTTR), respectively. This study presents the relationship between the STTR and DTTR to parametrise dynamics tyre models from static tyre test results. This modelling approach reduces the cost and time to parametrise tyre models by a factor of two, while significantly improving the accuracy of the PBS safety simulations. This approach offers a practical and cost-effective solution for parametrising tyres used by PBS heavy vehicles and improve the accuracy of PBS assessments.

Keywords: PBS (Performance Based Standard), Tyre modelling, Static Tyre Test Rig (STTR), Dynamic Tyre Test Rig (DTTR), generic PBS tyre

1. INTRODUCTION

Initially, the Performance Based Standards (PBS) scheme required that PBS vehicles be assessed with tyre models of the actual tyres the vehicle will operate with, thus restricting PBS vehicles to only operate with approved tyre sets. Operators and assessors raised concerns about the difficulty of obtaining reliable and accurate tyre data from the tyre Original Equipment Manufacturers (OEM) and suppliers. Tyre testing is costly, time consuming and different test facilities can produce significantly different results on the same tyre (Bruzsa & de Pont, 2021). On-road tyre field tests give the best accurate tyre data of how the tyre forces are generated in operation, however such tests are more difficult to control the test conditions (e.g. road roughness) and measurement precision compared to laboratory tests.

To mitigate the tyre modelling issues, the Australian National Heavy Vehicle Regulator (NHVR) reviewed the PBS tyre modelling approach and concluded a generic tyre model that scales the tyre characteristics of the discontinued Michelin XZA 11R22.5 tyre with a load rating of $2800\,kg$ is suitable for the majority of stakeholders (Bruzsa & de Pont, 2021), (Tiger Spider, 2021). The tyre characteristics are scaled based on the load rating to ensure consistency amongst assessors. This method neglects variations in tyre characteristics of different tyre brands, however, operators are allowed to change between tyres of the same size and load rating (Heavy Vehicle Industry Australia, 2020). A Pacejka 89 tyre model fit (Pacejka, 2006) must be utilised to minimise variability in interpolation of the forces and moments generated by the tyre during simulation.

Joyall Tyres (2019) compared the cornering stiffness vs. vertical load of seven 295/80R22.5 tyres to the equivalent PBS generic tyre of the same load index. Results show that the generic tyre under estimated the cornering stiffness of modern tyres by as much as 50% for vertical loads of $500\,kg$ and 25% for vertical loads of $4500\,kg$. The variation in stiffness characteristics of tyres from the same OEM is virtue of the OEM optimising tyre designs for the intended tyre use. For example, Goodyear (2021) strongly discourages the mismatch of tyres to their intended position (steer, drive and trailer), because each categories design is optimised for its intended purpose. Steer tyres are designed for responsive cornering, climbing curbs, low road noise and improved ride comfort. Drive tyres are designed to transmit the engine power to accelerate the vehicle and to brake the vehicle, so traction is prioritised. Trailer tyres are designed to minimise rolling resistance to reduce the fuel consumption and to minimise tyre scrubbing which leads to uneven tyre wear. Tyres constructed from similar materials will exhibit different characteristics due to the thread pattern (BFGoodrich, 2024).

Hjort, et al. (2021) investigated the tyre characteristics of 21 commonly used tyres on ice and dry asphalt to define and model standard tyres to be used for PBS assessments in the Swedish PBS Scheme. Results indicate that cornering stiffness increases by as much as $20\% - 50\%$ as the tyre wears in operation (Hjort, et al., 2021), (Fancher, et al., 1986), (Pottinger, et al., 1998). The cornering stiffness is comparable on ice and asphalt indicating the tyre belt stiffness, carcass stiffness and rubber stiffness are responsible for the cornering stiffness, whereas the surface friction is responsible for the peak force the tyre can produce (Chan, 2008), (Hjort, et al., 2021). Typically drive tyres have the highest cornering coefficient, followed by the trailer tyres with a slightly higher cornering stiffness then the steer tyres (Hjort, et al., 2021). Conversely, an older study by Pottinger, et al. (1998) found steer tyres had a higher cornering coefficient than drive tyres. This illustrates that tyre design and construction is continuously innovating. The force the tyre generates due to adhesion force and hysteresis force is inherent to the tyre design, construction and material (Chan, 2008), (Gillespie, 1992), as well as, the surface roughness, contact patch area and tyre penetration depth which influences the friction coefficient (Scholtz & Els, 2021), (Becker, 2021).

The Vehicle Dynamics Group (VDG) at the University of Pretoria in South Africa developed a Static Tyre Test Rig (STTR) to perform laboratory tyre tests efficiently with high precision and a Dynamic Tyre Test Rig (DTTR) to perform field tyre tests to accurately capture the tyres characteristics in operation. The STTR test surface is coated with a sand paper with a surface roughness Power Spectral Density (PSD) similar to the test track the DTTR is operated on. This ensures the saturation forces the tyre generates is consistent between the STTR and DTTR. Defining the relationship between the STTR and DTTR results is an on-going study. Becker (2021) suggests there exist a trigonometric relationship between STTR and DTTR which gives good correlation in the linear region for an agricultural tyre at $2.0\ Bar$. Additionally, VDG has developed a Wheel Force Transducer (WFT) to measure the forces and moments the tyre generates during tests. The STTR and DTTR use the same WFT, to ensure consistency of the measuring equipment for the different tests (Becker & Els, 2018).

2. AIM OF PAPER

This study proposes a cost effective tyre testing and modelling solution to support the South African PBS scheme. Laboratory-based tyre tests are conducted economically with high precision and accuracy to create a tyre model multi-body dynamics PBS simulation.

3. SCOPE OF PAPER

This study focuses on developing a cost-effective tyre testing and modelling approach to populate a PBS tyre database for commonly used tyres in South Africa. This study is performed on a GoodYear Regional RHT 385/65/R22.5 and covers the following areas:

- Laboratory-Based Testing: Tyre tests are performed on the STTR. Key measurements include lateral force, vertical force, lateral displacement, vertical displacement and contact patch dimension. A scientific relationship between the STTR and DTTR is defined to convert the lateral force vs. lateral displacement to lateral force vs. slip angle. Then, a Pacejka tyre model is created from the STTR test results and compared to the DTTR tyre test results of the study tyre obtained by Babulal (2015).
- Vehicle model validation: Experimental results from single lane change, constant radius, and sine sweep steer tests are used to validate the Vehicle Dynamics Group (VDG) tractor-semitrailer model developed in Adams View (Hexagon, 2024).
- High-speed PBS performance and tyre modelling cost: The validated vehicle model is used to perform high speed PBS tests to quantify the variation in performance due to the tyre models (DTTR, STTR and generic PBS). Finally, a cost comparison highlighting the improvement in accuracy of the STTR tyre over the generic PBS tyre at a fraction of the cost to parameterise the DTTR tyre.

4. TYRE MODELING

Static tyre tests are performed to measure the contact patch dimensions, vertical stiffness and lateral force vs lateral displacement. These tests covered a wide range of loads ([500, 1000, 2100, 3200, 3835, 4300, 5235, 6500, 7000, 8000, 9000, 10000] kg), at three different pressures ([5.9, 7.4, 9.0] bar). It is important to note that the static tests were performed several years after the dynamic tests had been completed. Since the dynamic tyre testing involves significant wear and in some cases damage the tyre, the static tests were conducted on a tyre that exhibited uneven wear. Additionally, the tested tyre had also been used operationally for years after the dynamic tests, thus minor variations in performance are expected. Only the 7.4 bar static test results are discussed, because the dynamic tests were conducted at 7.4 bar and similar trends are observed at 5.9 bar and 9.0 bar

4.1 CONTACT PATH TESTS

The contact patches show more wear on the outside of the tyre (top), resulting in an asymmetrical contact patch illustrated in Figure 1. At lower loads the contact patch exhibited an elliptical shape, which gradually transformed into a rectangular form as the load increases outlined in red. The elliptical shape grows faster in width than length as the load increases until the tyre shoulder (maximum tyre width) is reached. Then the elliptical contact patch transforms into a rectangular shape growing in length. The maximum load for the tyre at an inflation pressure of 7.4 bar is reached when the contact patch shape resembles a rectangle with sharp 90 degree edges. Beyond this point the contact patch maintained a rectangular shape that caves in at the centreline, with the length at the centre shorter than at the shoulders indicating the tyre is overloaded.

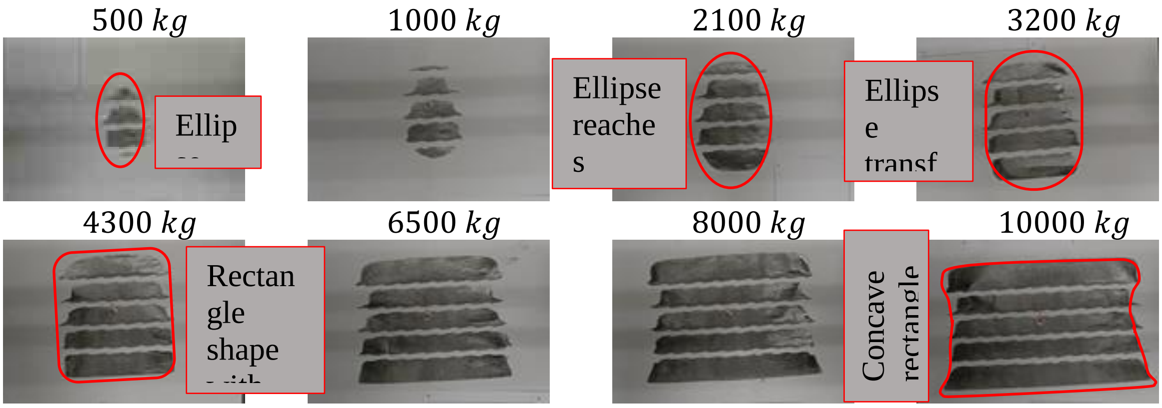

Figure 1 - Contact patches at an inflation pressure of 7.4 bar.

Figure 2 illustrates the relationship between contact patch dimensions as a function of vertical load. As pressure increases the contact patch area, length, and width decreases, illustrating the effect of inflation pressure on tyre patch dimensions. The contact patch area and length display a two gradient linear piecewise trend, while the width displays an exponential trend with an asymptote at the shoulder width of 285 mm for this tyre. At 7.4 bar the tyre shoulder is reached at approximately 4800 kg vertical load. The piecewise gradient distinctly change when the tyre shoulder is reached. Initially, the contact patch area expanded more in width than the length until the shoulders are reached, after which the width remained constant and the length continues to grow with increasing load. The transition occurs when the contact patch area and length piecewise gradients change when the maximum load is reached.

Similarly, the vertical stiffness tests show the tyre's vertical stiffness increases in a piecewise linear fashion with two distinct gradients before and after reaching the tyre shoulders as shown in Figure 3. Prior to the contact patch reaching the maximum width, the stiffness was primarily influenced by the inflation pressure and belt stiffness. Once the contact patch reaches the shoulders the tyre's sidewall contribute to the overall vertical stiffness. Also, the vertical stiffness is higher during the loading phase compared to unloading demonstrating hysteresis behaviour, because the tyre stores and dissipates energy as the tyre deforms and relaxes. Increasing the inflation pressure increases the vertical stiffness.

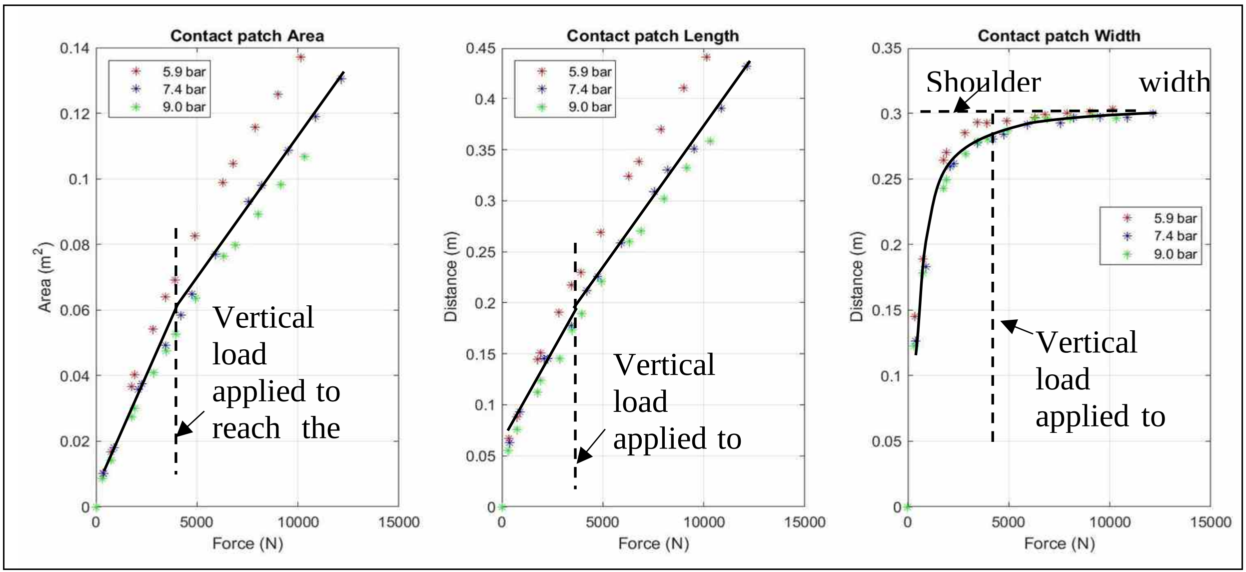

Figure 2 - Contact patches dimensions.

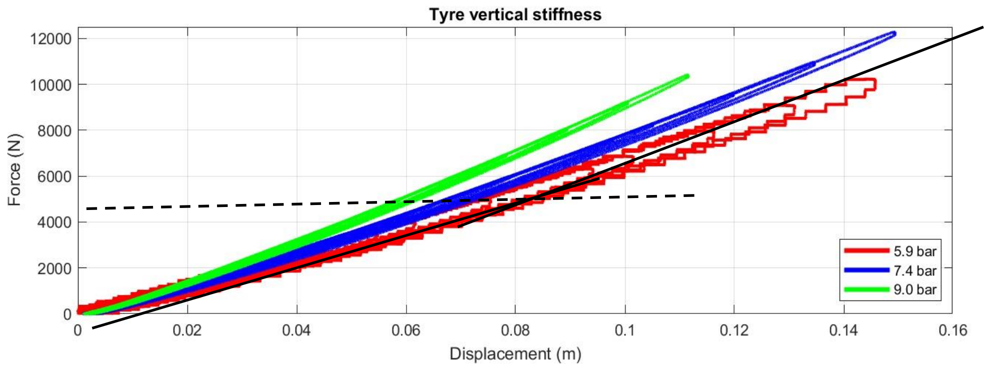

Figure 3 - Vertical stiffness.

4.2 LATERAL FORCE TESTS

This section describes the procedure to acquire tyre related data; the lateral displacement vs. lateral force obtained on the STTR shown in Figure 4(a) and the slip angle vs. lateral force obtained on the DTTR shown in Figure 4(b). The STTR is a laboratory-based system designed to measure tyre forces and moments under static tyre conditions. The contact surface is coated with sandpaper with the same surface roughness PSD to produces a friction coefficient similar to the test track used for the DTTR tests. A WFT mounted between the tyre and test bed measures the applied forces and moments on the tyre. A hydraulic actuator (max force of $30\,kN$ and $0.35m$ stroke) applies a vertical load (Fz) to the stationary tyre, by pressing the contact surface against the tyre. Once the target vertical load is reached, a second hydraulic actuator gradually displaced the contact surface laterally before the tyre is unloaded. Two laser displacement transducers are used to measure the contact surface vertical and lateral displacements. The DTTR is a field-based system designed to measure tyre forces and moments under dynamic free rolling tyre conditions. A WFT mounted between the tyre and test axle measures the applied forces and moments on the tyre. The vertical load on the tyre is increased by increasing the pressure of test axle's air suspension bellow to increase the axle's suspension displacement, thus bias the trailer load towards the test axle. A load cell on the test axle's air suspension measures the vertical force. Once the target vertical load is reached, the vehicle is accelerated and maintained at the target speed traveling in a straight line. Then, the steering arms are rotated to gradually increase the tyre slip angle from $0 - 12\ degress$. An encoder on the steer arms measures the tyre slip angle relative to the trailer.

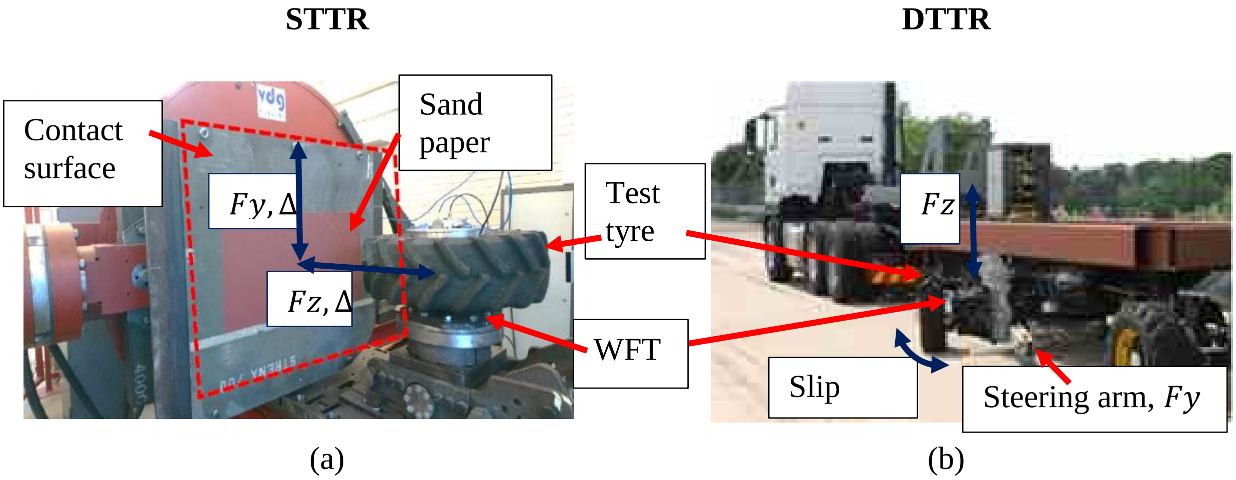

Figure 4 - Tyre test rigs (a) Static Tyre Test Rig (STTR) (b) Dynamic Tyre Test Rig (DTTR).

The STTR lateral displacement vs. lateral force tests were conducted under various vertical loads ([500, 1100, 2200, 3200, 4400, 6000] kg). As the lateral displacement increases, the tyre deforms, leading to an increase in lateral force. The lateral force continues to increase as the lateral displacement increases until the static saturation lateral force is reached, beyond which the tyre began to slide and the lateral force decreases to a dynamic saturation level remaining constant despite further displacement. Interestingly, as the lateral displacement is applied the lateral force increases and the vertical load gradually decreases. The reduction in vertical load is due to an increase in the effective length between the rim and contact patch centre as the tyre deforms. Also, as the contact patch moves laterally the sidewall stiffness decreases as the tyre deforms and in severe cases the outside sidewall buckles.

The tyre lateral stiffness exhibited two distinct stages as shown in Figure 5. The tyre lateral stiffness is inherent in the tyre construction and materials. These elements influence the elastic modulus of the tyre and is directly proportional to the inflation pressure. As the test surface is laterally displaced the tyre deforms while maintaining full contact with the test surface due to the adhesion and hysteresis force generated. As the lateral displacement increases the lateral force increases at a constant rate in stage one until the adhesion friction force saturates and decreases to zero. The hysteresis friction force continues to increase, but lags the adhesion forces. The total lateral stiffness decreases in stage two. As the tyre continues to deform the outer sidewall begins to lose contact with the test surface. As a result, the contact patch area decreases until the tyre begins to slide as the static peak friction force is exceeded. Then, the lateral force decreases to the dynamic force as the tyre slides. Increasing the vertical load increases the tyre penetration depth, hence the peak friction force the tyre can generate increases.

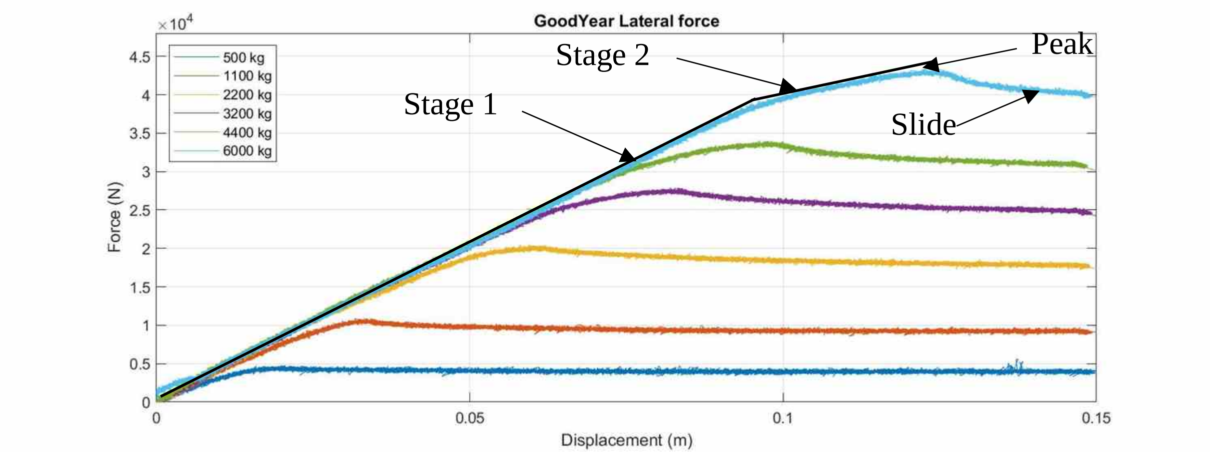

Figure 5 - Static Tyre Test Rig (STTR) lateral displacement vs. lateral force.

The static friction coefficient peaks around 0.75 for the correctly loaded tyres below the rated load of $4250\ kg$. For loads above the rate load the friction coefficient decreases, because the contact patch pressure distribution is concentrated around the contact patch boundary and the contact patch centre lifts of the surface. Because, the amount of rubber in contact with the surface decreases for overloaded tyres, the friction coefficient decreases despite the increase in tyre penetration depth and the surface roughness remaining the same. This illustrates the negative effect of over-loading tyre on the vehicles handling, because a reduction in cornering stiffness degrades vehicle stability.

4.3 PACEJKA MODEL PARAMETERISATION

To parameterise the Pacejka tyre model from the STTR tests, the lateral displacement (Δy) measured is transformed to a slip angle (α) using Equation 1. The trigonometric relationship between the lateral displacement and contact patch length (L) is scaled by the nonlinear function ($f(\frac{\Delta y}{L})$).

$$\alpha = f(\frac{\Delta y}{L}) \cdot \tan^{-1}\left(\frac{\Delta y}{L}\right) \qquad \textbf{Equation 1}$$

The asymptotic force (y_a) when the tyre slides, the peak force (D), and slip angle at peak force (x_m) shown in Figure 5 are used to calculate the Shape factors (C) by Equation 2. The slope between 0° and 2° is used to calculate the cornering stiffness (BCD) from the slip angle vs. lateral force test data. The Stiffness factor (B) and Curvature factor (E) are then calculated by Equation 3 and Equation 4, respectively.

$$C = 1 \pm \left[1 - \frac{2}{\pi}\sin^{-1}\left(\frac{y_a}{D}\right)\right] \qquad \textbf{Equation 2}$$

$$BCD = B \cdot C \cdot D \qquad \textbf{Equation 3}$$

$$E = \frac{B \cdot x_m - \tan\left(\frac{\pi}{2 \cdot C}\right)}{B \cdot x_m - \tan^{-1}(B \cdot x_m)} \qquad \textbf{Equation 4}$$

These initail Pacejka coeffiecents are used to determine the a0-a13 Pacejka paramneters to generate a load independent Pacejka 89 tyre model through least squares optimisation. The cost fuction is given by Equation 5, where Y and y represent the Pacejka tyre model friction coefficient and measured STTR friction coefficient, respectively , as shown in Figure 6. The friction coefficient is preferred over the lateral force, due to the vertical load variation during testing. The resulting STTR Pacejka tyre model is a compromise between capturing cornering stiffness and peak lateral force accurately as shown in Figure 7. Nevertheless, the STTR tyre Pacejka model correlates well with the DTTR tyre model as shown in Figure 8, indicating that cost-effective laboratory tests on a stationary tyre can closely approximate the behaviour of the same tyre under dynamic field conditions.

$$Cost = \sum \sqrt{[Y - y]^2}$$ **Equation 5**

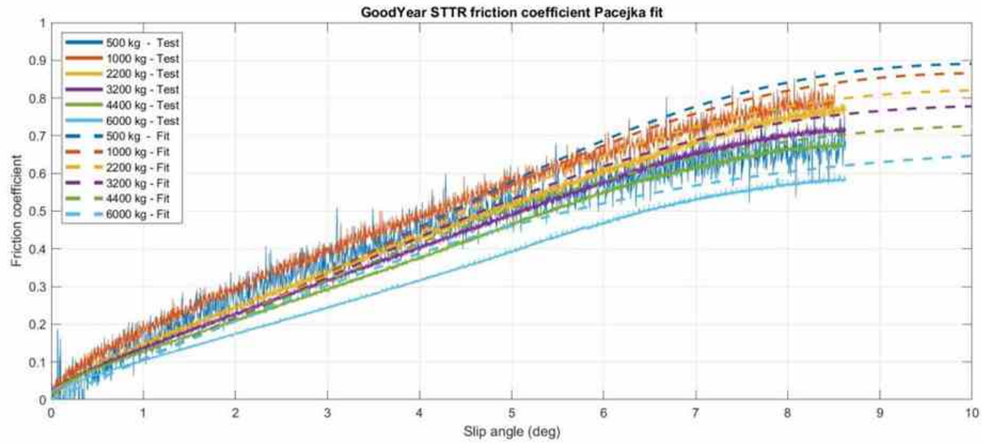

Figure 6 - Static Tyre Test Rig (STTR) (a) friction coefficient Pacejka fit.

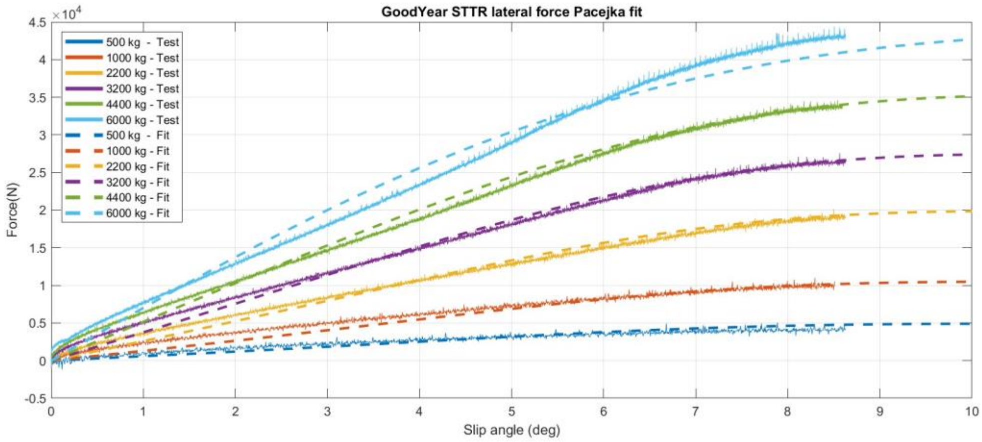

Figure 7 - Static Tyre Test Rig (STTR) lateral force Pacejka fit.

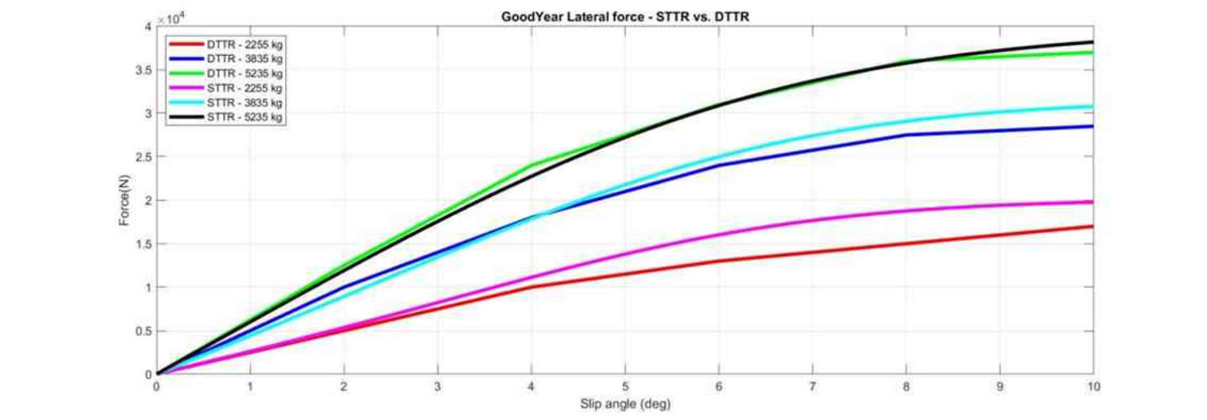

Figure 8 - Static Tyre Test Rig (STTR) and Dynamic Tyre Test Rig (DTTR) Pacejka tyre models at $7.4\ bar$.

5. VEHICLE MODEL VALIDATION

The tyre models are evaluated using the VDG tractor-semitrailer Adams View simulation model. The vehicle model is first fitted with DTTR tyre model and validated experimentally. Two Diamond Systems Helios Single Board Computer DAQs sampling at $1000\ Hz$ are used to record the sensor measurements on the tractor and trailer. Additionally, two Racelogic VBOX3i high-precision dual antenna GNSS with IMUs sampling at $100\ Hz$ are used as both sensors and data logger on the tractor and trailer.

Figure 9 shows the tractor-semitrailer performing a modified $4.5m$ lateral offset single lane change at $90km/h$. Figure 10 shows the vehicle performing a 30m constant radius while the vehicle speed is varied between $0 - 40\ km/h$. Figure 11 shows the vehicle performing a sine sweep manoeuvre at speeds $0 - 40\ km/h$ continuously exciting the vehicle and preventing the vehicle from reaching steady state In all tests the tractor-semitrailer model's lateral acceleration and yaw rate correlates well with the experimental measurements.

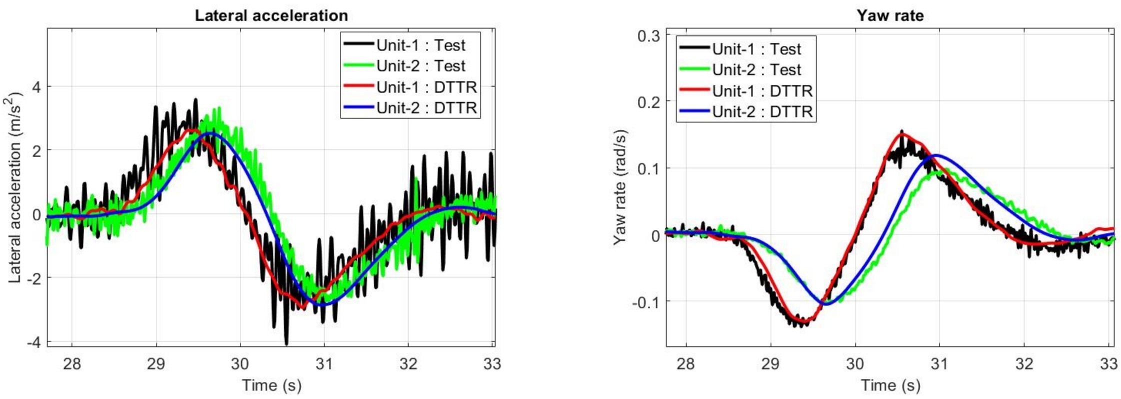

Figure 9 - Tractor-semitrailer performing a single lane change at $90\ km/h$

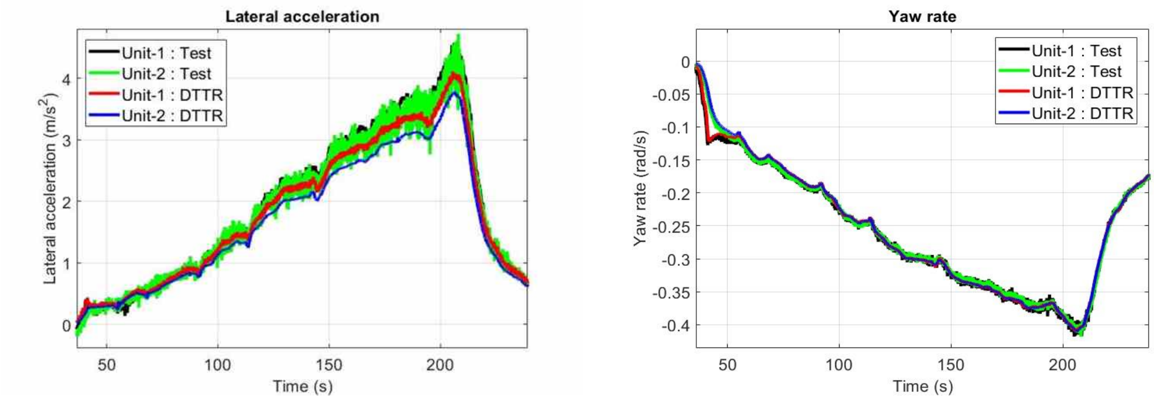

Figure 10 - Tractor-semitrailer performing a constant radius at $0 - 40\ km/h$

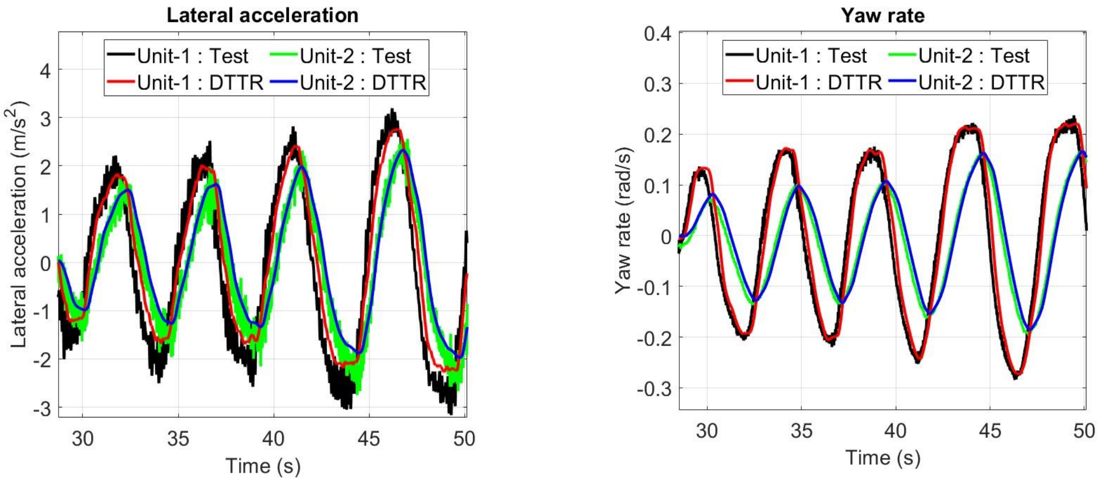

Figure 11 - Tractor-semitrailer performing a sine sweep at $0 - 40\ km/h$

6. HIGH SPEED PBS PERFORMANCE AND TYRE MODELLING COST

The validated VDG tractor-semitrailer model is used to quantify the accuracy of the STTR tyre (a cost-efficient alternative tyre model) and generic PBS tyre models, relative to the DTTR tyre model (benchmark tyre model generated from field test data). The vehicle is simulated performing high speed PBS tests to evaluate the influence of tyre model accuracy on PBS performance. The results are summarised in Figure 12 and Table 1. Both the STTR and generic tyres achieve a 7 % Yaw Damping Coefficient (YDC) error. The STTR tyre produces a similar High Speed Transient Offtracking (HSTO) and Rearward Amplification (RA) response to the DTTR tyre, achieving a 2 % and 3 % error, respectively. The generic PBS tyre over estimates the HSTO and RA response, achieving a 321 % and 10 % error, respectively. Overall the generic tyre model is less accurate than the STTR tyre mode, thus prematurely constraining the vehicle design and preventing the vehicle designer from optimising the payload efficiency. While the reasoning to simplify the tyre modelling approach practically makes sense, it is evident from the results that tyre models have a significant influence on PBS safety performance which is not directly proportional to the cornering stiffness. To parameterise a tyre model on the DTTR takes five days with one engineer and one technician compared to two days on the STTR with one engineer. The STTR tyre model closely approximates the DTTR tyre model at less than half the cost and time.

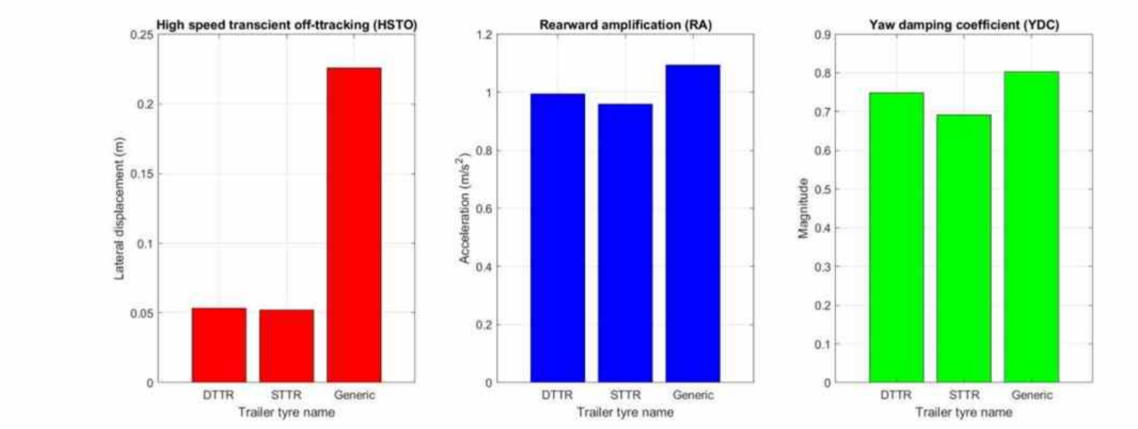

Figure 12 - High-speed PBS performance.

Table 1 - High speed PBS performance and tyre modelling cost.

	DTTR	STTR	PBS generic tyre
HSTO error (%)	NA	-2	321
RA error (%)	NA	-3	10
YDC error (%)	NA	-7	7
Time (days)	5	2	0

7. CONCLUSION

Tyre design is constantly innovating and different OEMs employ different design philosophies and materials to achieve the best tyre performance, thus expectedly there is a variation in characteristics of the tyres on the market. Tyre modelling has a significant influence on the high speed PBS performance of heavy vehicles, thus accurate tyre models are necessary to ensure that PBS heavy vehicles remain safe in operation. While dynamic tyre tests produce the most accurate data to generate tyre models, such tests cost more and take longer to conduct than static tyre tests. The VDG has developed tyre-testing equipment to characterise tyres cost efficiently. This study presents the relationship between the STTR and DTTR to parametrise dynamics tyre models from labotory tyre test results. This approach reduces the cost and time to parametrise tyre models by a factor of two, while significantly improving the accuracy of the PBS safety simulations. The STTR tyre model captures the tyre's nonlinear behaviour within 90% of the DTTR tyre measurements, but the STTR tyre gives significantly better accuracy than the generic PBS tyre at half the cost of the DTTR tyre.

8. RECOMMENDATIONS

- The STTR tyre model accuracy must be improved in the nonlinear region and the transient tyre behaviour at high speeds needs to be incorporated in the generic tyre model, especially considering the increasing prevalence of active control systems and trailer steering on PBS vehicles.
- Collaboration amongst stakeholders internationally contributing to a shared database will further reduce the cost of parametrising tyre models for PBS simulation. The inconsistencies between tests facilities can be addressed by testing the same tyre at all facilities and mapping the relationship between the facilities.

9. REFERENCES

Babulal, Y., 2015. *Large Tyre Testing and Modelling for Handling,* Pretoria: University of Pretoria.

Becker, C. & Els, S., 2018. *Static And Dynamic Parameterization Test Rigs For Large Tyres.* Kyoto, International Society for Terrain-Vehicle Systems (ISTVS).

Becker, C. M., 2021. *Parameterisation of Tyres with Large Lugs,* Pretoria: University of Pretoria.

BFGoodrich, 2024. *ONE TREAD DESIGN DOES NOT FIT ALL.* [Online] Available at: https://www.bfgoodrichtrucktires.com/tires/tires-101/tire-basics/tread-design-comparisons/
[Accessed 06 May 2024].

Bruzsa, L. & de Pont, J., 2021. *Managing tyre modelling in a PBS system.* s.l., 16th International Symposium On Heavy Vehicle Transport & Technology (HVTT).

Chan, B. J.-Y., 2008. *Development of an off-road capable tire model for vehicle dynamics simulations,* s.l.: Virginia Polytechnic Institute and State University.

Fancher, P. S., Ervin, R. D., Winkler, C. B. & Gillespie, T. D., 1986. *A factbook of the mechanical properties of the components for single-unit and articulated heavy trucks,* Ann Arbor,: University of Michigan Transportation Research Institute (UMTRI).

Gillespie, T. D., 1992. *Fundamentals of Vehicle Dynamics.* s.l.:Society of Automotive Engineers.

Goodyear, 2021. *What are the Different Types of Tyres for Trucks?.* [Online] Available at: https://www.goodyear.eu/en_gb/truck/knowledge-centre/truck-tyre-types-steer-drive-trailer.html
[Accessed 30 April 2024].

Heavy Vehicle Industry Australia, 2020. *PBS tyre report recommendations on the table.* [Online]
Available at: https://hvia.asn.au/pbs-tyre-report-recommendations-on-the-table/
[Accessed 14 August 2023].

Hexagon, 2024. *Adams.* [Online]
Available at: https://hexagon.com/products/product-groups/computer-aided-engineering-software/adams
[Accessed 11 May 2024].

Hjort, M., Kharrazi, S., Fröjd, N. & Siltanen, T., 2021. *Tyre modelling for high capacity vehicle simulations.* Qingdao, Heavy Vehicle Transportation Technology (HVTT) Forum.

Joyall Tyres, 2019. *Performance-Based Standards (PBS).* [Online]
Available at: https://www.joyalltyre.com.au/pbs-approved.html
[Accessed 04 November 2024].

Pacejka, H. B., 2006. *Tyre and Vehicle Dynamics.* 2 ed. Oxford: Elsevier.

Pottinger, M. G. et al., 1998. Force and Moment Properties of a small Sample of Tire Specifications: Drive, Steer, andTrailer with Evolution from New to Naturally Worn-Out to Retreaded Considered. *SAE International Journal of Commercial Vehicles*, 107(2).

Scholtz, O. & Els, P. S., 2021. Tyre rubber friction on a rough road. *Journal of Terramechanics,* 93(1), pp. 41-50.

Tiger Spider, 2021. *Tiger Spider.* [Online]
Available at: https://tigerspider.com.au/archives/75236
[Accessed 14 August 2023].