EFFECTS OF AGE AND WEAR ON THE STIFFNESS AND FRICTION PROPERTIES OF AN SUV TYRE

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HIGHLIGHTS

- Investigated the effects of tyre age and wear on tyre stiffness characteristics.
- Force vs. displacement characteristics have convincing dependencies on age and wear.
- Investigated the effect of tyre wear on longitudinal friction characteristics.
- Wear has a significant effect on the longitudinal friction.

ABSTRACT

Accurate tyre models are essential for all full vehicle simulation models. Tyre models are usually parameterised based on measurements on new tyres. This article performs a sensitivity analysis, based on experimental data, to determine the effects of age and wear on a 235/55R19 tyre's stiffness characteristics as well as the effect of wear on the tyre's longitudinal friction characteristics. A well-researched and documented method was used to artificially age the tyres. Static tests were performed periodically on the tyre to monitor the changes in stiffness characteristics. Tyres were also subjected to accelerated wear by performing repeated side force versus slip angle and longitudinal force versus slip tests on a coarse concrete surface. The results indicate that the vertical and longitudinal force versus displacement characteristics have small but convincing dependencies on the age and wear. While the aging process was a trustworthy method, the wear process created irregular lateral and circumferential wear which impacted results. Overall the effects of age and wear did not exhibit substantial enough influence on the tyre stiffness to merit a full tyre model update. However, the wear did have a significant effect, in the order of 10%, on the longitudinal friction of the tyre.

Keywords: tyre, age, wear, modelling

1 INTRODUCTION

The use of simulation models to lower the cost of the design process and shorten the time required to find an optimal design has become standard practise for Original Equipment Manufacturers (OEMs). Due to its high degree of non-linearity, the pneumatic tyre has always been a difficult component of a full vehicle to model accurately. As a result, extensive research has been performed on the modelling of a full tyre capable of simulation in all natural vehicle environments. These efforts involve validating a proposed tyre model with real test data collected on the specific tyre being modelled. Test data are almost exclusively obtained from new tyres after a short run-in period. Tyres do wear during testing which may affect results. During normal vehicle operation the tyre tread wears down which could therefore affect the ride and handling properties of the vehicle. Furthermore, although less well-known, the rubber in a tyre oxidises with the oxygen in the air used to inflate the tyre as well as the oxygen in the air surrounding the tyre (Baldwin, et al. 2005a). The effects of tread wear and tyre age on the characteristics of a tyre (e.g. vertical, longitudinal and lateral stiffness as well as friction coefficient) are not well understood.

All tyre models used in vehicle dynamics analysis require stiffness parameters in some form. FTire (Flexible Structure Tire Model) is a tyre simulation model available from Cosin Scientific Software (Munich, Germany) and is a good example of a tyre model that relies heavily on these stiffness parameters. The parameterisation of this model involves the use of test data acquired from the subject tyre, a Pirelli Scorpion Verde All Season 235/55 R19 105V, to identify specific parameters in the tyre model. Specific tests are recommended for the FTire parameterisation process by Gipser and Hoffmann (2016). These tests include quasi-static vertical, lateral and longitudinal force versus displacement characteristics as well as the footprint, geometry and Shore A hardness of the tyre. The material stiffness is crucial to the accuracy of these tyre models. If the material stiffness changes as a result of tyre wear and age, then the accuracy of the model in predicting worn or aged tyres also reduces.

This article investigates the extent of the changes in tyre stiffness properties due to aging and wear (using a static tyre test rig) as well as the effect of wear on the longitudinal friction (using a dynamic tyre test trailer).

2 Experimental Setup and Procedure

2.1 Subject Tyre

The subject tyre used to capture all the test data for the current study is a Pirelli Scorpion Verde All Season 235/55 R19 105V tyre (Pirelli & C. S.p.A, Milan, Italy) with a nominal inflation pressure of

250 *kPa* (2.5 *bar*). Due to the variety of tests completed four tyres were used. One tyre was used as a control tyre, another for aging only and two others for wearing. The tyres were all manufactured in the 10th week of 2015 at the Pirelli manufacturing facility in Carlisle, United Kingdom as part of batch number L598. The tyre is directional and has an asymmetric tread pattern. The tyre mass was 13.6 *kg* and together with the rim weighed 23.8 *kg.* The load corresponding to the 100% LI of the tyre at the nominal inflation pressure of 2.5 bar is 925kg (European Tyre and Rim Technical Organisation, 2003). All stiffness comparisons were performed at vertical loads of 50% and 100% of the LI rating i.e. 462.5kg and 925kg respectively, as well as, an inflation pressure of 2.5 *bar*. The vertical loads were selected as a result of FTire Parameterisation recommendations from Gipser and Hoffmann (2016). The inflation pressure is the recommended inflation pressure of certain vehicles equipped with this specific tyre and also the basic inflation pressure specified by the European Tyre and Rim Technical Organisation (2003). The original tread depth of the tyre was approximately 8 *mm*.

2.2 STIFFNESS TESTS

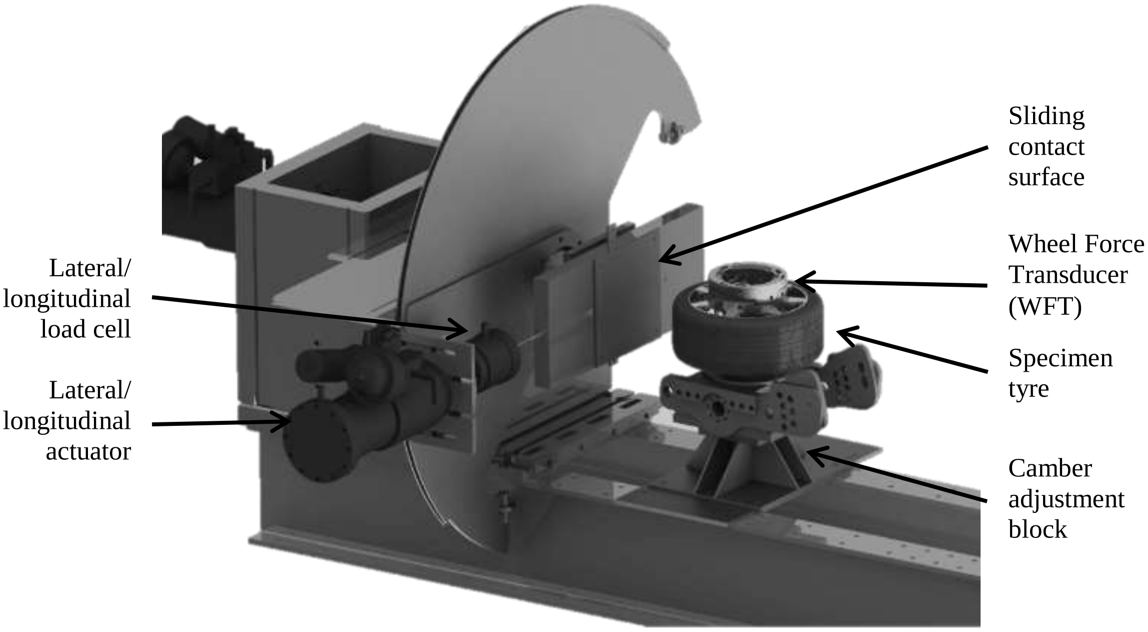

Figure 1 - Isometric view of STTR in position for vertical and longitudinal stiffness test

Tyre stiffness parameters are obtained experimentally using a Static Tyre Test Rig (STTR). Longitudinal force versus slip characteristics are obtained using a Dynamic Tyre Test Trailer (DTTT) which is also used to wear down the tyres.

Quasi-static stiffness tests were conducted on the STTR shown in Figure 1. Figure 2 illustrates how the STTR operates when testing the vertical and longitudinal stiffnesses of the tyre. The dotted arrow indicates the direction of travel when testing only the vertical stiffness. Components labelled with round dots and 'x' markers are the components of the STTR that move in the vertical direction of the tyre. When testing the longitudinal stiffness, the tyre is vertically loaded and then held at a specific load whilst the sliding longitudinal assembly, indicated by all those components connected with the round dots, moves in the direction of the dashed arrow. A P80 Corundum sandpaper contact surface was used for all tests to create a high friction coefficient (approximately equal to one) and thus a large longitudinal displacement prior to the tyre slipping. The tyre displacement is measured with Acuity model AR700 road profiling laser displacement transducers (Schmitt Industries, Inc., Portland, Oregon, USA) (Acuity 2016) indicated by the plus signs. These are accurate displacement transducers with a resolution of 0.01 *mm* across the span of 200 *mm.* All tyre forces and moments are measured using a 6-component wheel force transducer (WFT). In addition, single component longitudinal and vertical load cells measure these two force components directly.

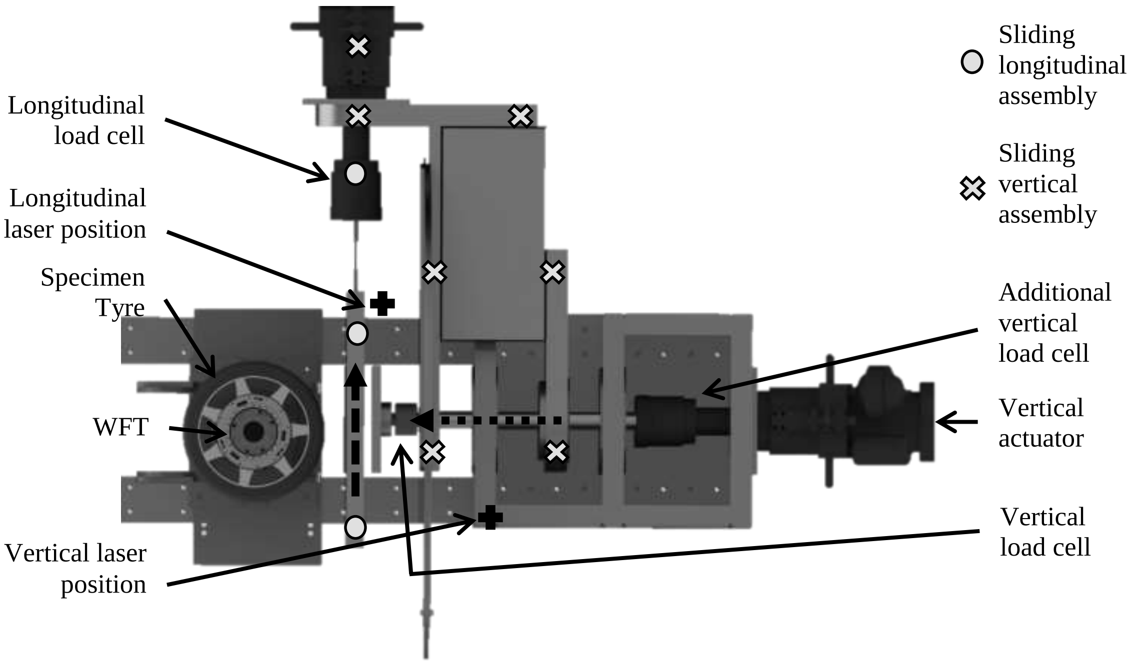

Figure 2 - Plan view of STTR in position for vertical and longitudinal stiffness test. WFT is Wheel Force Transducer.

The STTR uses two hydraulic actuators, namely a 100 *kN* actuator for actuating in the vertical direction and a 40 *kN* actuator for actuating in the lateral or longitudinal direction depending on the orientation. Each actuator is fitted with a Linear Variable Differential Transformer (LVDT) displacement transducer and coupled with a Universal Low Profile (ULP) load cell (labelled as the vertical and lateral/longitudinal load cell in Figure 1 and Figure 2) of equivalent force range to that of the actuator used. Tests are performed on a flat surface as well as a mild steel cleat (20 *mm* by 20 *mm* cross-sectional dimensions) applied in the centre of the tyre in the lateral and longitudinal direction across the whole width and length of the tyre respectively. Figure 3 shows the laterally mounted cleat pressed against the tyre.

Figure 3 – Pressing of a 20x20mm mild steel laterally mounted cleat against the tyre.

The repeatability and accuracy of the tests completed using the STTR was investigated by the comparison of several cycles of various tests and it was found to be better than ±1% of the vertical deflection at 50% of the Load Index (LI) of the subject tyre. Any variation in test results of less than ±1% is therefore deemed insignificant and attributed to the repeatability of the test equipment.

The aging and wear analyses produced a substantial number of tyre force versus displacement curves. An easily interpretable and relevant method is needed to quantify the changes in these stiffnesses. In this study, the percentage change in the deflection of the tyre required to reach 50% of the tyre's LI is used to compare the different test results. This produces a quantifiable value which is easily interpreted as it is a physical measurement. The load of 50% of the LI is also representative of typical normal operating load experienced by the tyre.

2.3 LONGITUDINAL FORCE TESTS

The longitudinal force versus slip tests are obtained on the DTTT shown in Figure 4. The trailer is towed behind a large vehicle and consists of two axles where the front axle is used as the test axle. It employs air suspension on the test axle to easily change and control the vertical load on the test tyres. Electric actuators are used to continuously change (sweep) the slip angle of the test tyres, pneumatically actuated disk brakes are used to control the braking. The WFT from the STTR is also used to measure the six components of force at each test tyre. Longitudinal slip is measured using cameras and Digital Image Correlation (DIC) techniques (Botha and Els 2014).

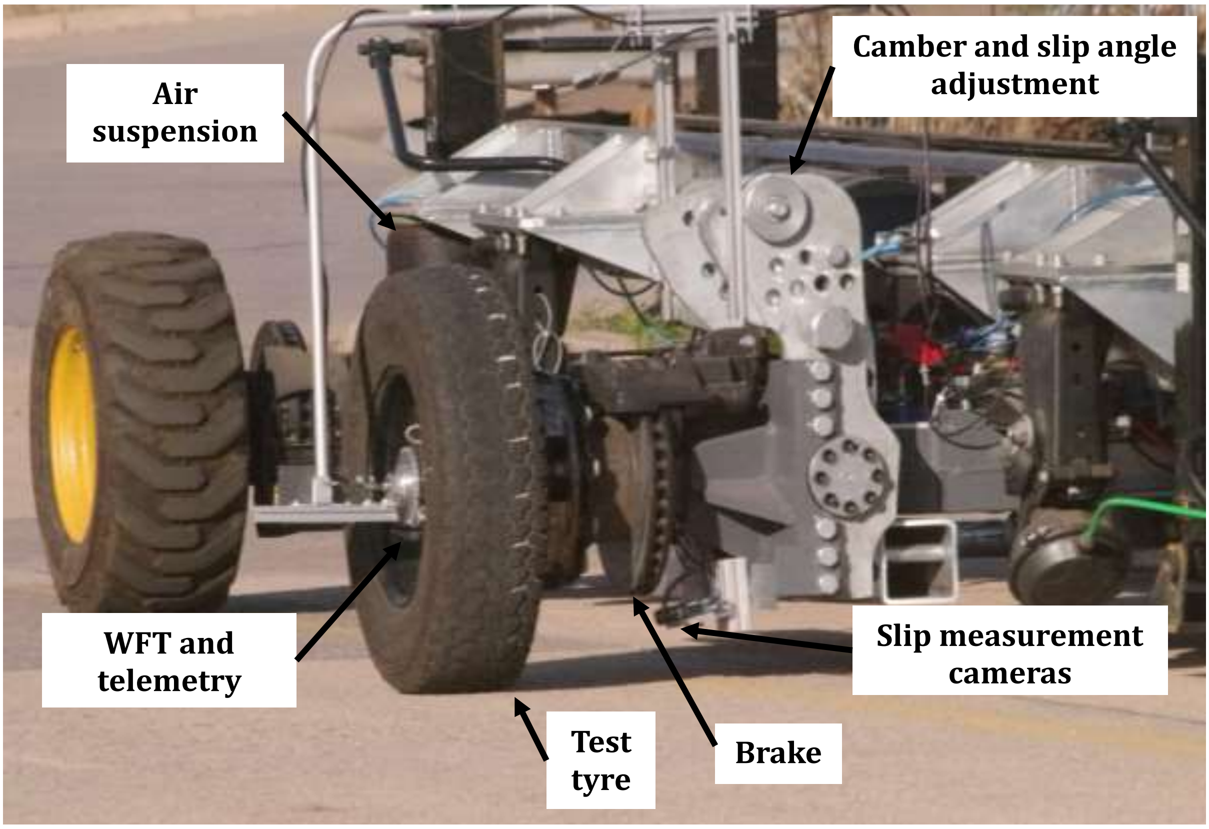

Figure 4 – Dynamic Tyre Test Trailer (DTTT). WFT is Wheel Force Transducer.

2.4 AGING PROCEDURE

Baldwin 2003, Baldwin et al. (2005a, 2005b), Baldwin and Bauer 2008, Bauer et al. (2005) and Ellwood et al. (2004) have published several papers on the artificial aging of tyres using static oven aging. Their research effort is significant and includes the testing of a large number of passenger car tyres aged in the field from different regions and in different climates. Baldwin et al. (2005a, 2005b) describe methods of artificially aging tyres using the same evaluation method compared to the field aged tyres in Baldwin et al. (2005c, 2005d). This comprehensive method for accelerating the age of a tyre was methodically followed in order to acquire aged tyres as similar as possible to those aged in the field.

Based on the recommended aging procedure in Baldwin et al. (2005a, 2005b), the tyre in this study was filled with a gaseous mixture of 50% Nitrogen and 50% Oxygen at 3.5 *bar* (maximum inflation pressure) and artificially aged in an oven at 65°C for approximately 8 weeks. This procedure ensured the tyre of concern would have approximately equivalent rubber properties to those of a four year old tyre used in the field in Phoenix, Arizona in the USA according to Baldwin et al. (2005a). During the aging process the tyre was tested periodically on the STTR after 1, 2.5, 4 and 8 weeks of aging. The tyre was allowed sufficient time to cool down and was deflated and re-inflated with air each time after removal from the oven before any testing was performed.

The Shore A hardness is one of the easily updatable parameters in an FTire model but was also anticipated to be a property of the tyre that would change with the aging of the tyre. This expectation is based on results discussed in Kataoka et al. (2003) where the Shore A hardness of the tread rubber on a specific spare tyre was observed to increase by 10 over a period of approximately 250 weeks stored and protected from direct sunlight in temperatures between 45 and 50 $^{\circ}C$. The Shore A hardness was measured using a Bondetec BS-392A Shore A Hardness tester (Guangzhou Amittari Instruments Co., Ltd., Guangzhou, China). The hardness was measured at 10 marked locations around the tyre, five on the tread and five on the sidewall. The measurements were repeated approximately 15 times at each location. This process was repeated each time the tyre was removed from the oven for testing.

2.5 WEARING PROCEDURE

Two tyres were abrasively worn using the DTTT, on a coarse concrete surface, where tread would be noticeably removed in less than 50*km* of effective travel of the tyre. This was achieved by applying a combination of periodic longitudinal braking and lateral slip angle sweeping. Data were captured on the DTTT in between these procedures to quantify the effects of wear on the longitudinal force versus slip characteristic of the tyre.

After each round of wearing, the profile of the tyre was measured with a road-profiling laser displacement transducer and the stiffness tests were performed on the STTR. The tyre was tested at 4 different wear states, namely new, 28.6% worn, 50% worn and 100% worn. The static test data acquired included properties such as the mass and tread depth as well as the Shore A hardness on the sidewall and tread of the tyre. The same set of stiffness data were acquired each time as was done with the aged tyre.

In order to remove any possible errors in the measurements acquired, the effect of running the tyre in was also investigated. This involved vertically loading the new tyre on the tyre test trailer and towing it for a distance of approximately 20*km* whilst the tyre was rolling freely (i.e. no braking or slip angle applied). This tyre was tested before and after the running in process.

3 RESULTS

3.1 AGING

3.1.1 Shore A Hardness

The Shore A values for the sidewall and tread were measured for each round of tests after the tyre had been removed from the oven and allowed to cool down to room temperature. Figure 5 illustrates the change in average Shore A values for the sidewall and the tread over time. The sidewall gives clear indications of a change in hardness after the first round of aging, whereas the tread hardness does not change by any noticeable amount until after approximately two weeks of aging. Thereafter the total change of six percent relative to the new tyre value for the tread is substantial.

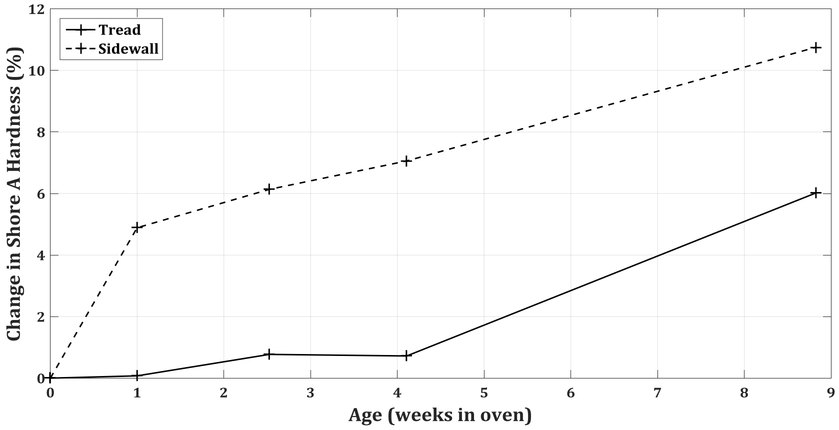

Figure 5 - Percentage change in Shore A hardness at the tread and sidewall whilst aging

3.1.2 Vertical Stiffness

Figure 6 shows the various vertical stiffnesses on a flat surface with zero camber angle as the tyre was aged. The change in stiffness is not consistent. The tyre appears to get softer after the first week of aging before it starts getting stiffer in the weeks that follow. This could be due to the final curing or breaking of incomplete bonds in the chemical structure of the tyre as it is heated up for initial in-service operation. Figure 7 shows the changes in deflection at 50% and 100% of the LI compared to the results of the tests of the new tyre.

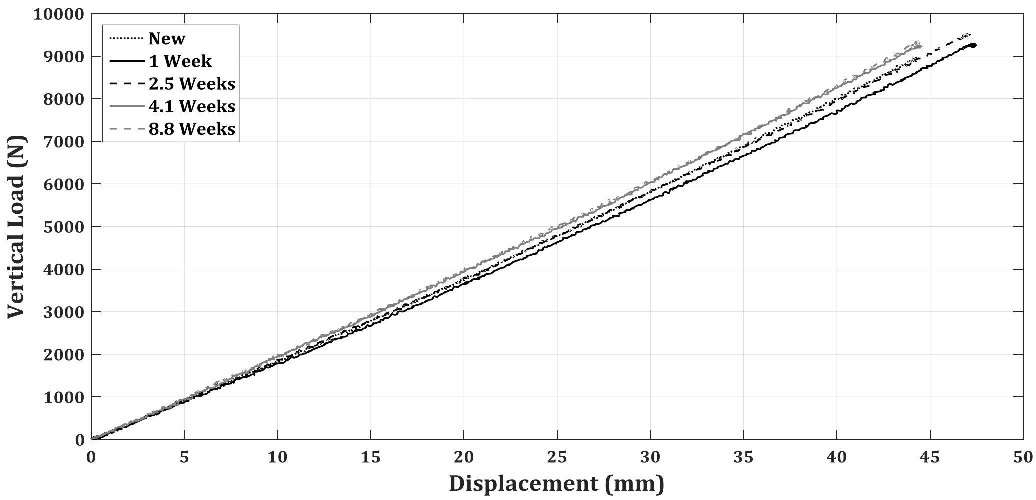

Figure 6 - Vertical stiffness changes on a flat surface as the tyre ages

Figure 7 indicates changes in deflection at the two load cases considered. Relative to the deflection required to reach the same load with the new tyre, the percentage change is more substantial at the lower load than at the higher load. Despite the initial 'softening' of the tyre, the stiffness appears to consistently increase for an additional three weeks of aging after which the 1% threshold is exceeded after 4 weeks. Thereafter the rate drops substantially, almost as if it had stopped changing completely.

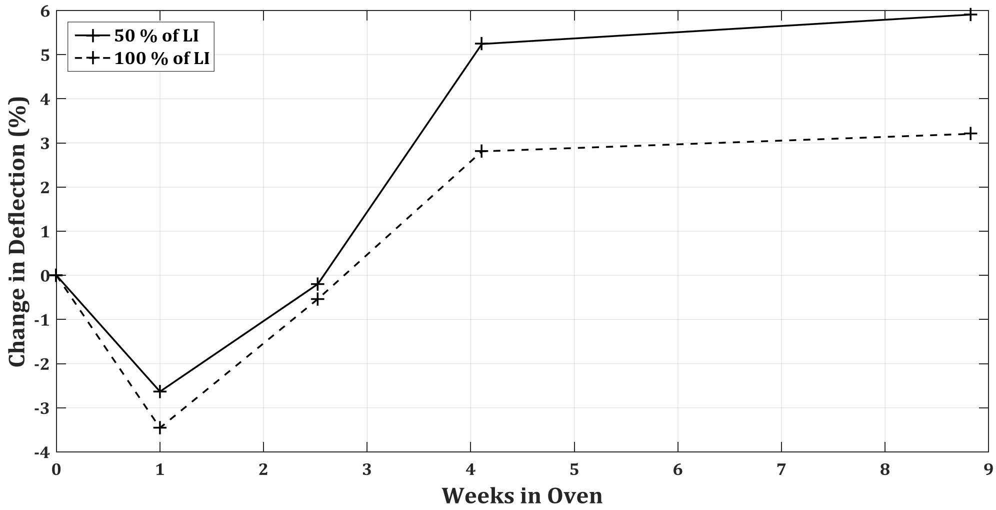

Figure 7 - Percentage change in vertical deflection of aged tyre on a flat surface

3.1.3 Longitudinal Stiffness

The longitudinal stiffness is the relationship between the longitudinal displacement (displacement of plate) and the resulting longitudinal force. Test data of the longitudinal stiffness test is shown in Figure 8. As with the vertical stiffness the change in deflection is also used to capture the change in longitudinal stiffness. The change is deflection is determined at 50% of the maximum longitudinal force. The change in deflection initially reduced by -3.5% after 1 week which after it increases to above 8% at 8.8 weeks.

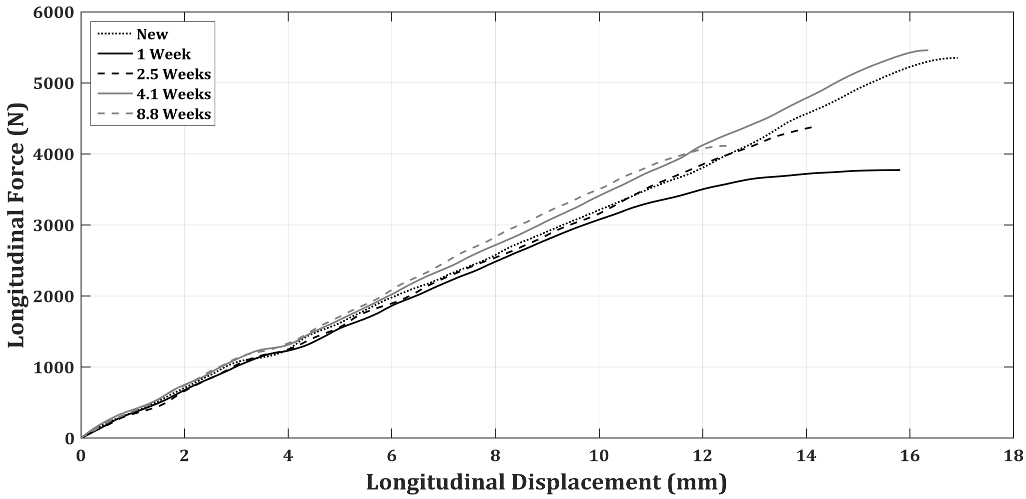

Figure 8 - Changes in longitudinal stiffness as the tyre ages

3.1.4 Summary of Aging Effects

The results of the tyre stiffness tests illustrate a variety of changes in the characteristics of the tyre as it ages. The comparison between the stiffnesses was conducted through the relative change in the deflection detected at vertical loads of 50% and 100% of the LI conducted on a flat plate, with a lateral cleat, with a longitudinal cleat and at -4º camber. The longitudinal stiffness is given as a relative change in longitudinal deflection at 50% of the maximum longitudinal force on a flat plate. Results for all tests conducted are summarised in Figure 9. The horizontal dash-dotted lines were added to indicate the equipment accuracy thresholds of ±1%. The average change in deflection at each aging interval is also indicated. The average change is determined as the average between all data points of all tests at a specific aging state. This is added to indicate what the average stiffness change of the tyre for all different tests are. A linear trend line is added to indicated the overall trend in the stiffness change. There is a clear upward trend in all the measured parameters with changes of between 2% and 8%. The changes exceed the equipment measuring accuracy in all tests after approximately 4 weeks of aging, indicating that the changes are induced due to the tyres aging and not due to the experimental repeatability. It should be noted that the effect may differ for larger tyre with more rubber compound and different tyre constructions.

Of all the parameters measured, the Shore A hardness indicated a clear and substantial trend and since this parameter is very simple and quick to measure, it is a good candidate to be considered for FTire model updating. The change in the shore A hardness, specifically of the sidewall, is similar compared to the change in tyre stiffness.

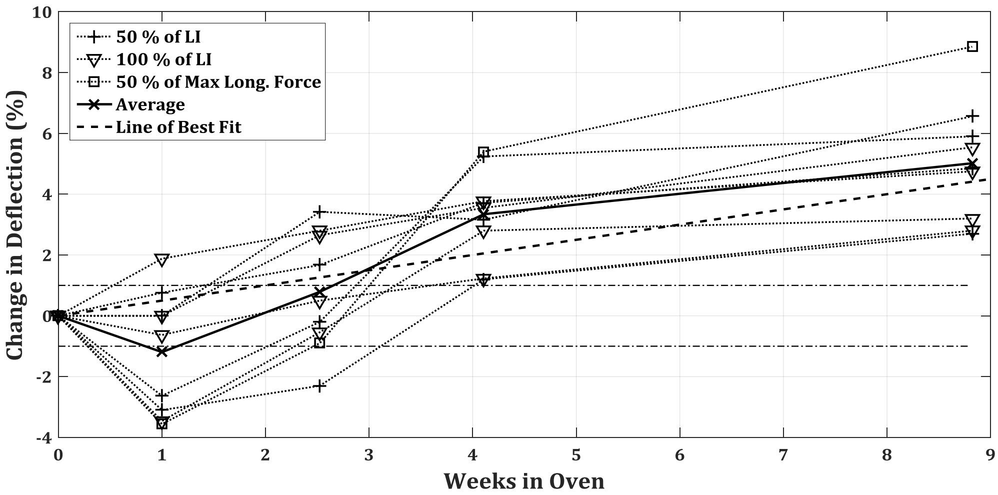

Figure 9 - Percentage change in deflection of all test data with averages and a line of best fit. The horizontal dash-dotted lines indication the equipment thresholds of ±1%.

3.2 WEAR

The wear test data were not as reliable as the aging data due to the method used to wear the tyres. The abrasive nature of this method yielded several flat spots on the tyre and caused severe feathering of the tread. Tread feathering occurs when the tread ribs are worn lower or smoother on the one side and higher or sharper on the other (Bridgestone, 2018). Nevertheless the most noticeable test results are presented in the form of the tyre mass, tread profile and the longitudinal stiffness change.

The initial tread depth of a new tyre is 8mm. Figure 10 shows the change in the tread profile at one cross-section on the tyre as the tyre was worn. The irregularity of the tread depth across the tyre is evident. Also of note is that the amount of tread worn away between the wearing stages was also irregular. After the last round of wearing it is also clear that the tread was completely removed in close proximity to the two middle tread grooves.

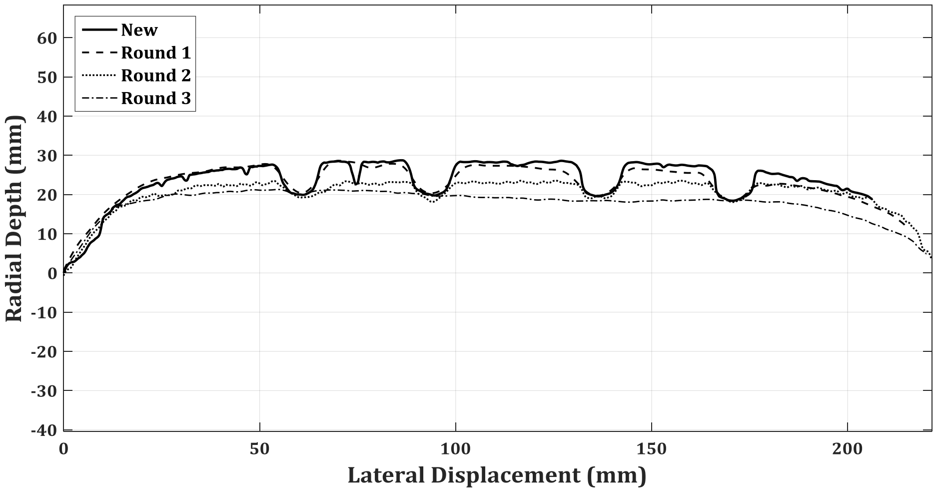

Figure 10 - Change in tread profile as the tyre is worn

3.2.1 Mass

The mass of the tyre was determined after each round of testing. Table 1 shows how the tread wear results in a substantial change in the mass of the tyre. The average wear in the centre and shoulder are provided as an indication due to the inconsistent wear obtained.

Table 1 - Change in mass of tyre as the tyre is worn

Round	Tyre Mass (kg)	Δ Tyre Mass (kg)	Percentage of Total Tread Wear (%)	Average Wear in Centre and Shoulder (mm)
0	13.625	0	0	0, 0
1	13.025	0.6	29	2, 1.5
2	12.575	1.05	50	4, 3
3	11.525	2.1	100	8, 6

From the tread profile indicated in Figure 10, it is clear that, after the final stage of wearing, the tread depth was equal to zero. Despite severe flat spots and some wear which exposed the carcass of the tyre, there were also sections that still had 50% of the original tread. The assumption was made that tread wear is linearly related to change in mass. Instead of attempting to measure an average tread depth around the tyre circumference, wear was simply scaled between 0 and 100% by using the change in mass as indicated in Table 1 as the tread wear around the circumference of the tyre was too inconsistent. Therefore, after the first stage of wearing, the tread wear was calculated to be 29% and after the second stage the tread wear was 50%. After the final stage, tread wear was defined to be 100% or fully worn.

3.2.2 Run-in Longitudinal Stiffness

To ensure a solid baseline for the results presented in this section, an additional test was conducted whereby a new tyre was run-in over a 20 *km* stretch at approximately 6.5 *kN* vertical load, or approximately 70% of the LI. The tyre was free-rolling and did not generate any lateral force during the run-in period. This was completed to investigate if the properties, such as vertical stiffness of the tyre, noticeably change in the first few kilometres of use. The idea was that the initial stretching and breaking of weak rubber bonds would occur in this initial stage of use and could thus skew the results of the worn tyre tests, should there be any clear changes. Sandberg (2008) ran tyres in over a distance of 300 *km* and up to a maximum speed of 140 *km/h* prior to any testing conducted on a tyre. Unfortunately the motivation behind this procedure was not provided and neither was the vertical load of the tyre.

The most substantial changes in stiffness due to this run-in process occurred with the longitudinal stiffness (Figure 11). In this case, at 50% of the maximum longitudinal force attained, the run-in tyre's longitudinal displacement was approximately 6.7% greater than that of the new tyre value. This is a considerable change in longitudinal stiffness.

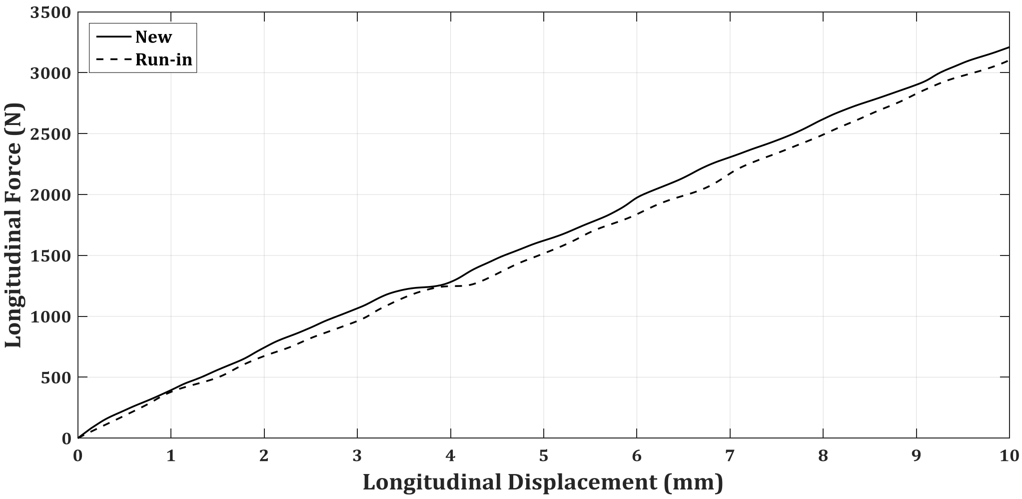

Figure 11 - Comparison of longitudinal stiffness for a new tyre and a run-in tyre

3.2.3 Longitudinal Stiffness

Figure 12 shows the change in the longitudinal stiffness as a function of the wear of the tyre. The longitudinal stiffness results showed the most substantial changes in stiffness from all the tests performed – almost double those of the other stiffnesses tested. In Figure 12 the new tyre is for a non run-in tyre, to better compare the effect of tread wear the effect of the running in process is also included. Figure 13 shows the relative change in the tyre deflection compared to a new tyre as well as run-in tyre. Relative to a new tyre (solid line) the deflection at an applied longitudinal load of 50% of the maximum longitudinal force decreases. However, once the effect of running in the tyre is incorporated the adjusted deflections shows an initial increase in deflection. This increase is mainly due to the increase in deflection experienced from the running in process. This results in a smaller effect of wear on the change in deflection, and therefore stiffness, once a tyre has been run-in.

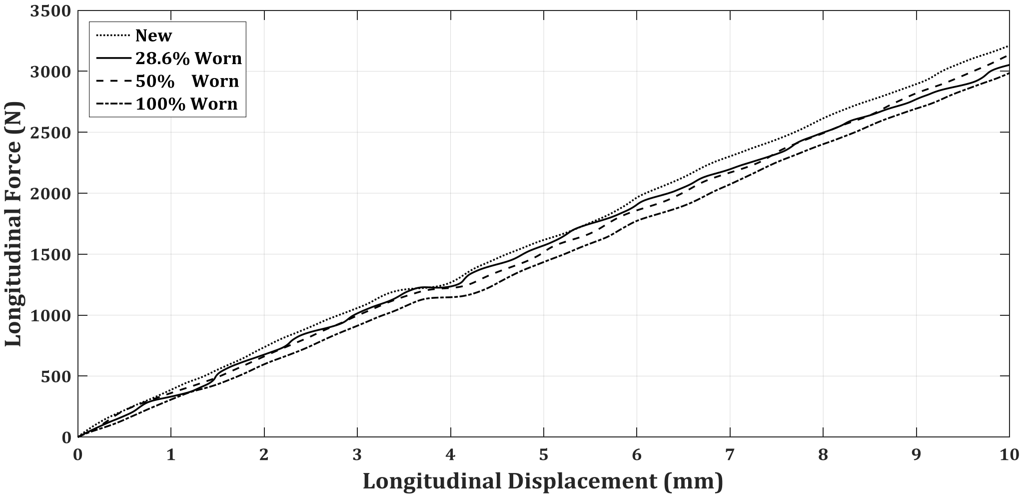

Figure 12 - Changes in the longitudinal stiffness as the tyre is worn

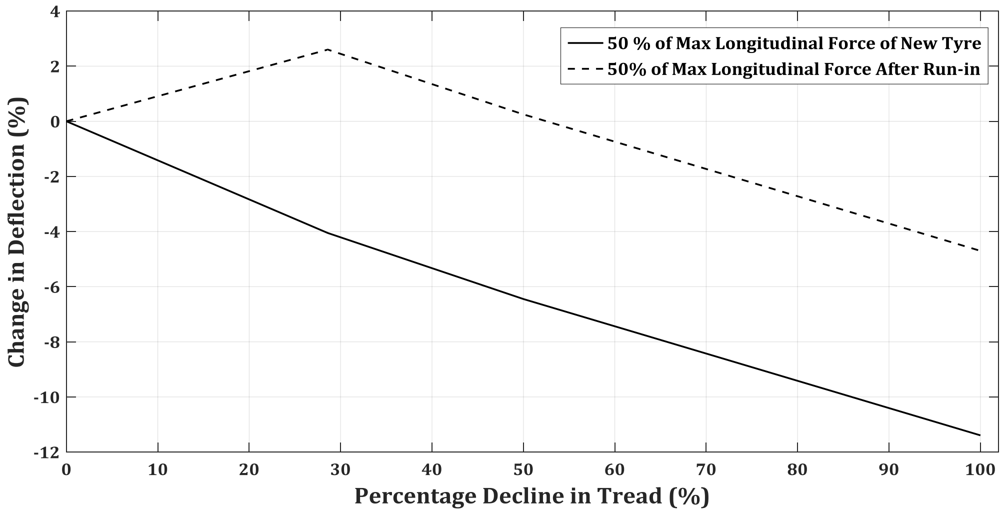

Figure 13 - Percentage change in deflection at 50% of the maximum longitudinal force acquired

3.2.4 Summary of effect of wear on tyre stiffness

Figure 14 summarises the effect of wear on stiffness. The figure shows the change in vertical deflection calculated at 50% and 100% of the LI conducted on a flat plate, with a lateral cleat, with a longitudinal cleat and at -4° camber. The figure also shows the change in longitudinal deflection determined at 50% of the maximum longitudinal force. The dashed threshold lines for the equipment measuring accuracy are easily exceeded on almost all accounts, however, no clear trend presents itself from the full set of data. The completely scattered behaviour of the results obtained demonstrate that further investigation is required on this topic with a much-improved method of realistically wearing the tyre. The changes are substantial in some cases (up to 11%) and should not be ignored.

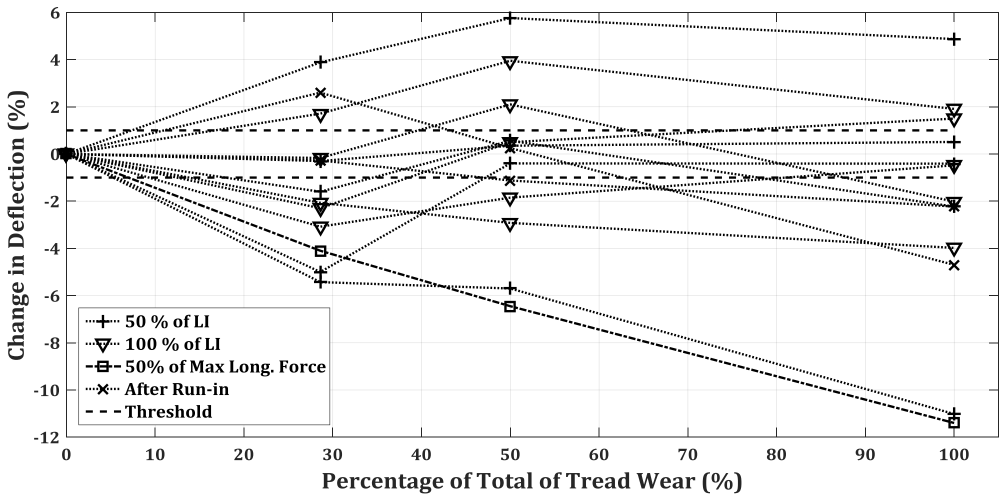

Figure 14 - Percentage change in deflection of all test data

A very clear trend was apparent in the comparison between the new tyre and the one that had been run-in. These effects were clear on tests at 0° camber on a flat surface and with the laterally mounted cleat as well as most noticeably with the longitudinal stiffness. These changes were shown to be sufficient to motivate a model update however it is a very difficult parameter or adjustment to quantify and therefore also difficult update in the FTire model.

3.2.5 Effect of wear on longitudinal force versus longitudinal slip characteristic

The effect of the tyre wear on the longitudinal force versus longitudinal slip characteristic of the tyre was determined using the dynamic tyre test trailer. The tyre was tested at the same inflation pressure of 2.5 *bar*, vertical load and camber when new and in wear state at Round 3 (see Figure 10). During braking tests, where the braking force was gradually increased, the vertical and longitudinal forces were measured using the wheel force transducer. As it is difficult to accurately control the vertical force on the tyre, the coefficient of friction (i.e. $\frac{longitudinal\ force}{vertical\ force}$), for different vertical forces, for the new and worn tyre are shown in Figure 15. The figure clearly shows that there are substantial differences in the longitudinal coefficient of friction between the new and worn state. During the testing both the vertical load and the slip vary due to small oscillations of the tyre test trailer. The variation in vertical force results in the maximum coefficient of friction to vary within a range. The response of the brake system is also too slow to enable accurate slip control. These effects make direct comparison difficult. Hence, to better obtain a quantitative difference in friction coefficient a longitudinal Pacejka 89 tyre model (Bakker et al, 1989) was fitted to both the new and worn tyre data.

The fit was obtained by means of a gradient based optimisation algorithm using the measured slip, vertical load and longitudinal force during the braking test. A comparison of the fit to measured data is created by taking the measured slip and vertical force to produce an estimated longitudinal force which is compared to the actual measured force. This comparison is shown in Figure 16. Figure 16 shows that the Pacejka fit accurately captures the longitudinal force as a function of vertical load and slip for both the new and worn tyre. Due to the small variations in the vertical force the Pacejka fit does not appear as a function which should provide a single longitudinal force for a specific slip. It should be noted that the plots are actually three dimensional with slight variation in the vertical force hence the multiple points at a specific slip point.

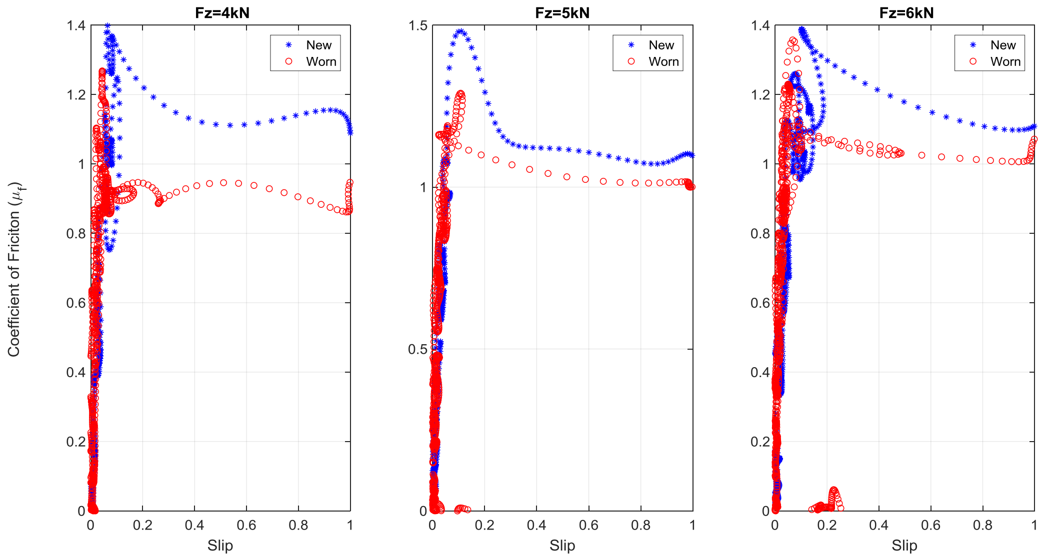

Figure 15 – Comparison between the measured coefficient of friction for the new and worn tyre at different vertical loads

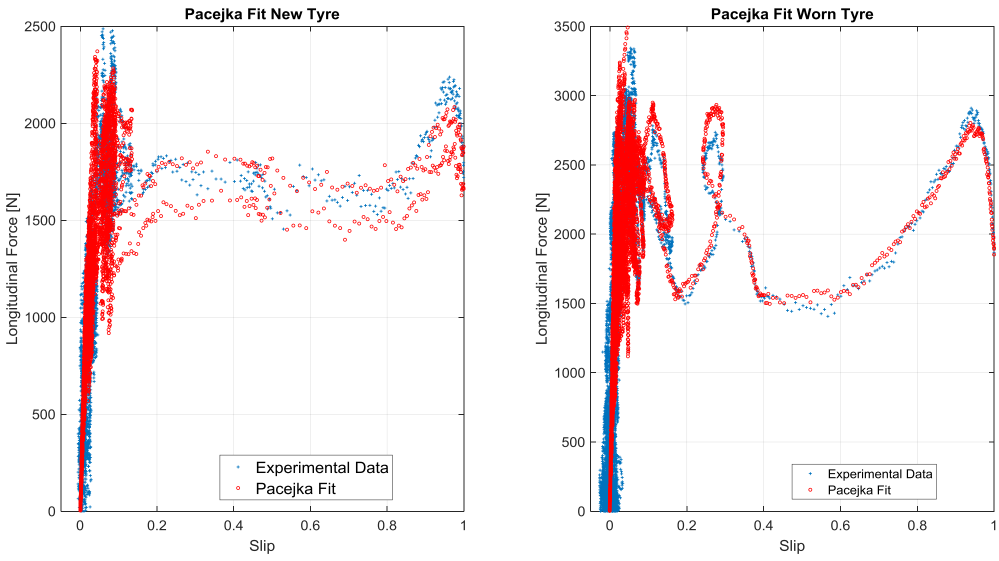

Figure 16 – Comparison of longitudinal Pacejka 89 tyre model fit to measured data.

The Pacejka fits for both the wear states are shown in Figure 17. Figure 17 makes a quantitative difference easier to obtain and indicates that the friction coefficient for the worn tyre is between 10 and 15% lower than for the new tyre. This difference corresponds to that observed in the measured data indicated in Figure 15 measured data. The change in friction coefficient could partially be attributed to the uneven wear of the tyre tread and not necessarily just a change in viscoelasticity of the rubber but is nonetheless substantial.

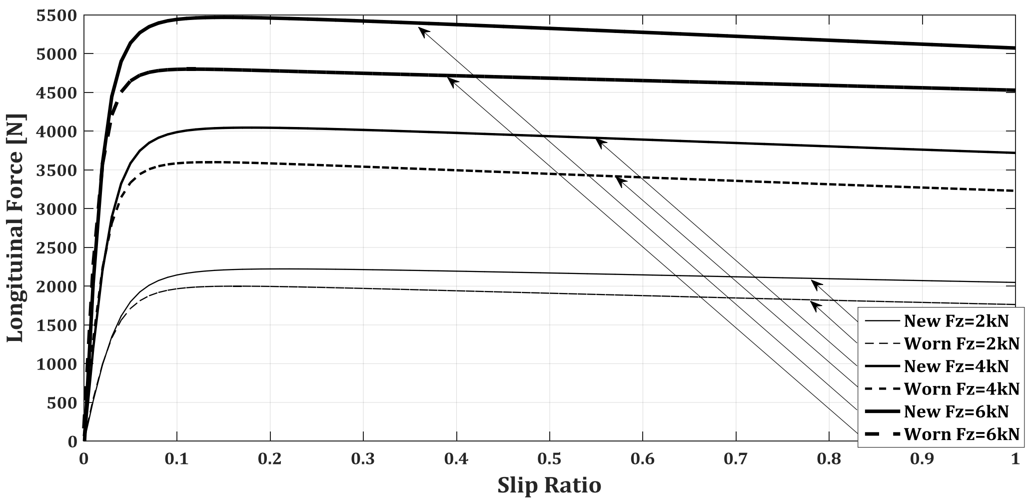

Figure 17 – Comparison between Pacejka 89 models of new and worn tyre at different vertical loads.

4 CONCLUSION

This article successfully quantified the effects of aging and wear on the stiffnesses as well as the effect of wear on the longitudinal friction coefficient of a tyre. The static testing equipment accuracy threshold of ±1% was exceeded by the aging and wearing effects presented. Some additional influences such as the run-in period of a tyre were also presented and demonstrated noticeable changes to the tyre stiffnesses. This proved to be a period in the operational life of the tyre which needs to be accounted for if percentage change in deflection more accurate than 1.5% in the tyre model are desired.

The largest expected difference in stiffness between a severely aged tyre and a new tyre is approximately 5%.

In the case of the wear investigation, irregularities in the wearing procedure made it difficult to identify a trend in stiffness changes. The most noticeable effect was observed in the case of the longitudinal stiffness due to its potential independence from the irregularities in the tread depth at the contact patch. In this case an error of 11% could be expected if the wear of a tyre is ignored in the tyre model. The observed trend does however warrant further investigation.

The effect of wear on the longitudinal friction of the tyre was found to be between 10 and 15%. This is a large change and can have a substantial effect on the braking and ABS analysis performed in simulation.

The changes in tyre properties due to aging and wear are generally small but not insignificant. Running in the tyre before testing results in a better tyre model with little additional effort or cost. Further research into the aging effect on the longitudinal and lateral force generation can be performed to determine whether these effects are also significantStudies on different tyre construction and size can also be performed to see whether larger changes are observed.

5 REFERENCES

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