# COMPUTATIONAL ANALYSIS OF A SOUTH AFRICAN MOBILE TRAILER-TYPE MEDIUM SIZED TYRE TEST RIG

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To support the South African National Defence Force with their vehicle mobility needs, the CSIR has begun characterising tyres by using a medium, trailer-type, tyre test rig. Two different Pacejka tyre models were generated using two independent methods and it was necessary to validate the tyre models against physical tests. The computational simulations gave partial credit to the tyre models. However, the dynamic lane change results were in poor agreement with the simulations, although the two Pacejka models were in good agreement with each other. The disagreement questioned the traditional tyre characterisation method. It was also necessary to determine how the Pacejka tyre models compared to the physical tyre in the vertical direction, by conducting Belgian paving runs. The one model performed better than the other, although these models are not suited for high frequency vertical dynamics.

## 1 INTRODUCTION

### 1.1 Background

The Council for Scientific and Industrial Research (CSIR), Landward Sciences (LS), has been contracted by the Defence Research and Development Board (DRDB), via the Armaments Corporation of South Africa (ARMSCOR), in order to establish and maintain a vehicle mobility capability to support the defence force. In the last few years, LS has made progress to meet this objective by gaining experience in tyre characterisation and other areas of vehicle mobility. Although LS are currently experienced in generating lateral dynamics, handling, tyre models, the aim is to eventually become competent in modelling high frequency, vertical dynamics based, off-road tyre models.

LS are the custodians of a medium trailer-type tyre test rig, which is capable of characterising medium sized tyres (~16 in. rim size), and a large trailer-type tyre test rig, which is capable of characterising large sized tyres (~20 in. rim size). The University of Pretoria's Vehicle Dynamics Group (VDG) are in possession of a small tyre test rig which is capable of characterising SAE Mini Baja type tyres (~10 in. rim size). This family of South African tyre test rigs are shown in Figure 1.

*Figure 1: Small (VDG), medium and large tyre test rigs (CSIR)*

Each tyre test rig operates on the same design principle. The tyre on the right-hand-side of each rig is isolated via a sub-frame which is connected to the main frame by load cells. There are two lateral load cells (one in front and one behind the wheel hub), three vertical load cells (connecting the front, middle and rear of the sub-frame to the main-frame), and one longitudinal load cell (at the front of the sub-frame). The load cells are intended to measure the lateral, vertical and longitudinal loads on the tyre, as tyre slip is varied with the use of linear actuators. The large tyre test rig enables the adjustment of camber. The medium tyre test rig enables the adjustment of camber and caster via an adjustable hub designed by Kuduntwane (2014) [1] as part of his M.Tech. (Mechanical Engineering) degree, at the

CSIR, with supervision from VDG. The small, medium and large tyre testers make use of 0.5 ton, 5 ton and 10 ton load cells, respectively. Finite payloads (steel plates) can be mounted on top of each rig in order to vary the normal load on the test tyre.

LS is currently capable of determining the parameters required to generate Pacejka 89 [2] and Pacejka 2002 [3] Magic Formula (MF) tyre models used in the MSC ADAMS environment. These computational tyre models are generated from tyre characterisation test data and by determining the parameters required for fitting curves to the data.

## 1.2 Motivation

Mobility is required in order for a military vehicle to maintain tactical advantage in combat scenarios. If the vehicle has significant armour protection but has no mobility, it is just a matter of time before an enemy attack is able to penetrate a vehicle's armour. For this reason, it is important to ensure/predict vehicle mobility of military vehicles on various terrain conditions.

For the case of wheeled land-based vehicles, the tyre is the only component that communicates with the terrain. All forces and moments that are transferred to the vehicle originate at the tyre contact patch. Therefore, it is important to accurately predict the forces and moments transferred from the tyre contact patch to the rest of the vehicle, in order to predict how the vehicle will behave.

Computational modelling in multi-body dynamics software plays an important role in predicting vehicle dynamics due to it being safer than physical testing of prototypes; enabling savings in time and money; and it has proven to be acceptably accurate for research and design purposes [4, 5]. A number of vehicle dynamics studies can be performed in the computational environment before a single prototype is constructed. For this reason, LS makes use of MSC ADAMS and similar multi-body dynamics software to support the defence force. In order to model vehicle dynamics, accurate tyre models are required.

The need of this study was to evaluate the quality of the lateral dynamics Pacejka MF computational tyre models that could be generated by using the medium tyre test rig, in order to learn whether accurate tyre models can be generated. It was also of interest to evaluate how the Pacejka 2002 and Pacejka 89 computational tyre models perform in the vertical direction compared to the physical performance. The instrumented tyre test rig was towed across the Belgian Paving track at Gerotek. The same Belgian Paving, which was scanned by VDG [6], was imported into MSC ADAMS and the computational tyre test rig traversed the scanned Belgian Paving. The forces measured experimentally were compared to the computationally measured forces.

## 1.3 Objectives

In order to validate a computational Pacejka tyre model generated from data obtained from the medium tyre test rig, the objectives of the investigation were to:

1) Compare the computational tyre behaviour with the physical tyre behaviour as measured during the "static" characterisation tests. "Static" characterisation, in this context, refers to the tyre test rig moving at a constant velocity at different tyre orientations. That is, each of the characterisation tests was performed at a single unique combination of slip angle, camber angle, tyre pressure and payload. None of these parameters were modified during the "static" tests (although the rig was travelling at constant velocity). By replicating the "static" characterisation sweep tests in computational simulation, it was hoped to obtain the same tyre forces (computationally) that were measured during the physical characterisation sweep tests.
2) Compare the dynamic performance of the computational tyre, while mounted on the medium tyre test rig, with a physical dynamic test – a modified SAE Lane Change.
3) Evaluate whether the Pacejka 89 and Pacejka 2002 models perform satisfactorily, for LS purposes, in the vertical direction.

# 2 METHODOLOGY

## 2.1 Static tyre characterisation tests

A Dunlop GranTrek AT1 235/85 R 16 tyre was used for the investigation. Various tests were conducted at various payloads (based on the tyre load index) and camber angles (by using a specially designed adjustable hub). Lateral slip angle was varied from zero slip, in increments, in the toe-in direction, via a slip linkage mechanism and a linear actuator. That is, each test was conducted at a constant velocity and a single slip angle. Tyre pressures were monitored and maintained during the tests. The tests were conducted on a straight flat track (zero degree inclination) at the Gerotek Testing Facilities, in dry conditions. Lateral and vertical load cells were used to monitor the tyre forces transferred to the main-frame of the test rig. An HBM eDAQ (electronic data acquisition system) was used to capture the load cell data. The rig was towed by a large South African Army Military (SAAMIL) vehicle. Tyre deflection and tread wear was also recorded during the characterisation tests. Figure 2 describes this setup.

*Figure 2: Test setup(with actuators and adjustable hub) for the tyre characterisation of the Dunlop GranTrek AT1 tyre*

These static characterisation tests were replicated within MSC ADAMS with the Pacejka MF 89 and 2002 curve-fitted tyres (which were derived from the tests). The MSC ADAMS/CAR Tire Data Fitting Tool was used to fit the Pacejka 2002 curves to the measured data. The Pacejka 89 curves were generated by determining the coefficients of the MF curve fit, by using an in-house developed Matlab script. Figure 3 shows the MSC ADAMS replication of the characterisation tests.

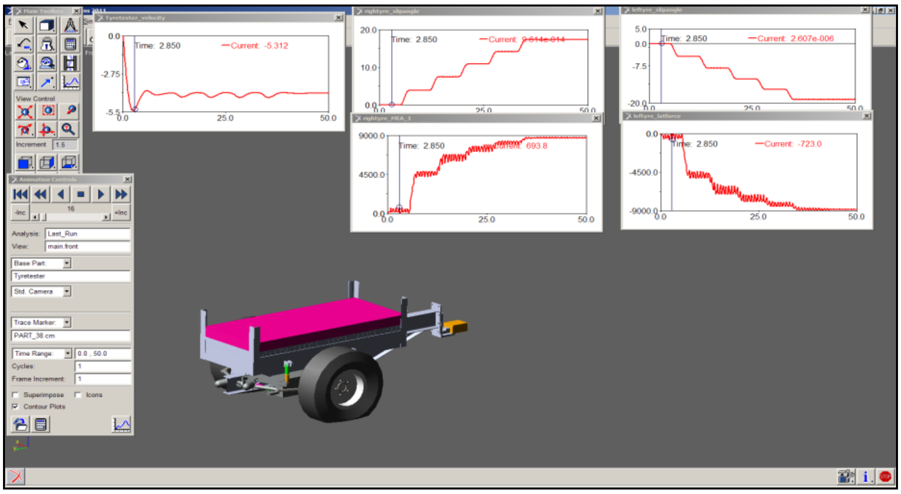

*Figure 3: ADAMS replication of tyre characterisation tests*

### 2.2 Lane change dynamic validation tests

Subsequently, modified SAE Lane Changes [7] were conducted, with the tyre test rig, in order to compare how the computational rig compares to the physical rig in a dynamic event. The test rig was towed through the lane change path with the SAAMIL vehicle. The tow hitch path was traced with a VBOXIII which also recorded the speed of the event. The same tow path was replicated within MSC ADAMS. Figure 3A and Figure 3B shows the physical and simulated lane change setup, respectively.

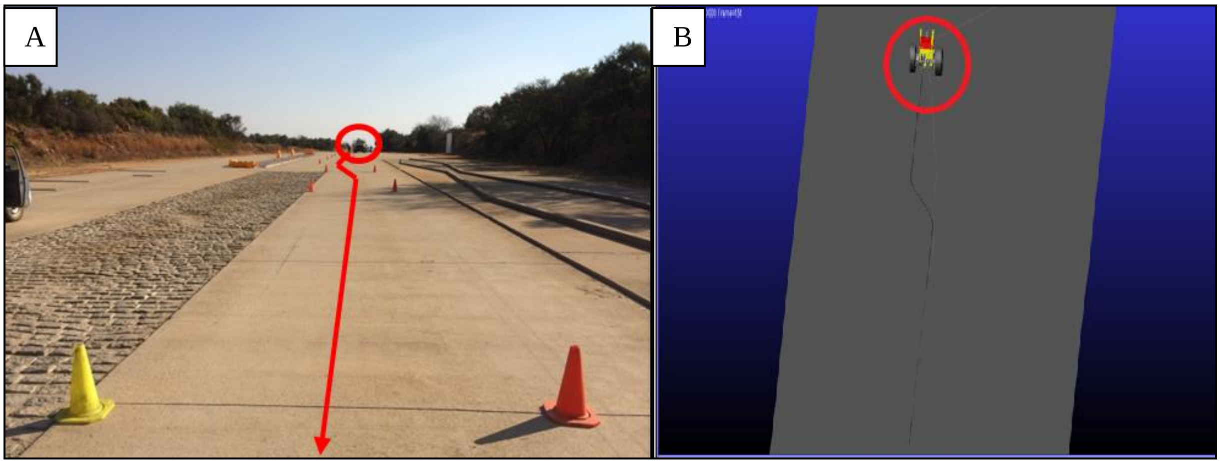

*Figure 4: Physical and simulated lane change*

Accelerometers, which were mounted at the Centre of Gravity (CG) of the tyre test rig, were used to measure the lateral acceleration of the rig. A measure was created at the CG of the ADAMS model in order to measure the lateral acceleration of the model.

The SAE J2179 single lane change standard specifies that the test vehicle travels at a speed of 88 km/h along a straight path, for 100 m. Thereafter, the vehicle is to perform the lane change within a manoeuvring section (longitudinal distance) of 61 m with a lateral displacement of 1.46 m. These dimensions were designed to provide a steer axle lateral acceleration of approximately 0.15 g (g = 9.81 $m/s^2$), for a medium sized passenger car [7]. However, in the validation tests, the manoeuvring section was reduced to 16 m, since the SAAMIL-test-rig setup could only be tested at lower speeds. The best reduced test speed was found to be 65 km/h, since the tyre test rig does not have a suspension. This test speed generated tyre test rig lateral accelerations of up to 0.12 g, at the CG.

### 2.3 Belgian paving tests

To investigate the vertical dynamics performance of the computational Pacejka 89 and 2002 tyre models, the physical and computational tyre test rigs were towed over the physical and computational Gerotek Belgian Paving tracks. The vertical load cells on the physical test rig recorded the forces experienced by the tyre. The accelerometer at the CG of the rig measured the vertical dynamics of the rig. The vertical forces could be measured on the tyre component of the computational model. To measure the vertical acceleration, a measure was created at the CG of the computational test rig.

## 3 RESULTS

### 3.1 Static characterisation tests

The tyre slip angle was changed, incrementally, from zero-toe toward the toe-in direction, in-between each test. The lateral force data measured at each slip angle (for various tyre payloads and camber angles) were used to generate the Pacejka 89 and Pacejka 2002 MF curves (representations of the physical tyre behaviour). It is important to note that the same data was used in two independent methods to obtain the Pacejka 89 and Pacejka 2002 characteristic curves. An in-house Matlab code was used for the Pacejka 89 curves and the ADAMS TDFT tool was used for the Pacejka 2002 curves. Two ADAMS tyre input files were created based on these regression analyses (one for each model).

To validate whether the physical tyre and the computational ADAMS tyre behaved the same, the characterisation tests were replicated in ADAMS (at the same speeds and slip angles) and the lateral force vs. slip angle curves were obtained. Since the physical static results and the computational static results were in reasonable agreement (as shown in Figure 5), one can conclude that the computational tyre and physical tyre behave approximately the same, in the lateral direction. Figure 5 represents one of 12 tests which were conducted, which all showed similar agreement. However, the dynamic performance of the physical and computational tyres differs significantly, as will be shown in the next section.

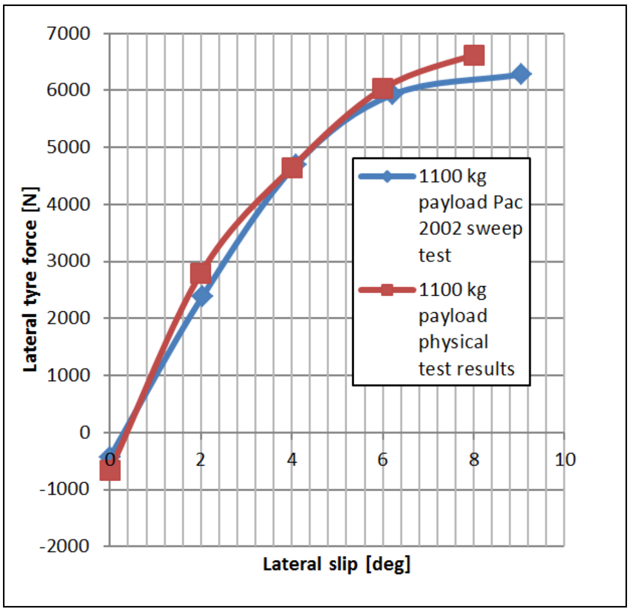

*Figure 5: Computational and physical static characterisation lateral force results*

### 3.2 Dynamic lane change validation tests

The reason behind generating Pacejka 89 and Pacejka 2002 MF tyre models for ADAMS is to be able to model dynamic manoeuvres of military vehicles, for LS purposes. For this reason, the tyre models generated, as described in previous sections, had to be validated. To do this, dynamic lane change manoeuvres (as described previously and at various conditions) were conducted at the Gerotek Test Facilities.

The results from the dynamics lane change simulations show that, although the two tyre models were generated in two completely different and independent methods (Pacejka 89 via in-house processing script; Pacejka 2002 via automatic ADAMS TDFT tool), they were in good agreement. This indicates that the curve fitting / tyre model generation process (the regression analyses) was performed correctly and accurately based on the static characterisation data. However, the two agreeable computational results differed significantly from the measured dynamic lane change validation tests. This is shown in Figures 6 – 8, which show the lateral acceleration of the tyre test rig during the lane change manoeuvres from the computational simulations and the physical measurements. Figure 6 – 8 also show the standard deviations (SD) of the physical tests (based on three tests for each case). The tyre pressure, camber angle, road surface fiction and test speed have been intentionally excluded from the results shown.

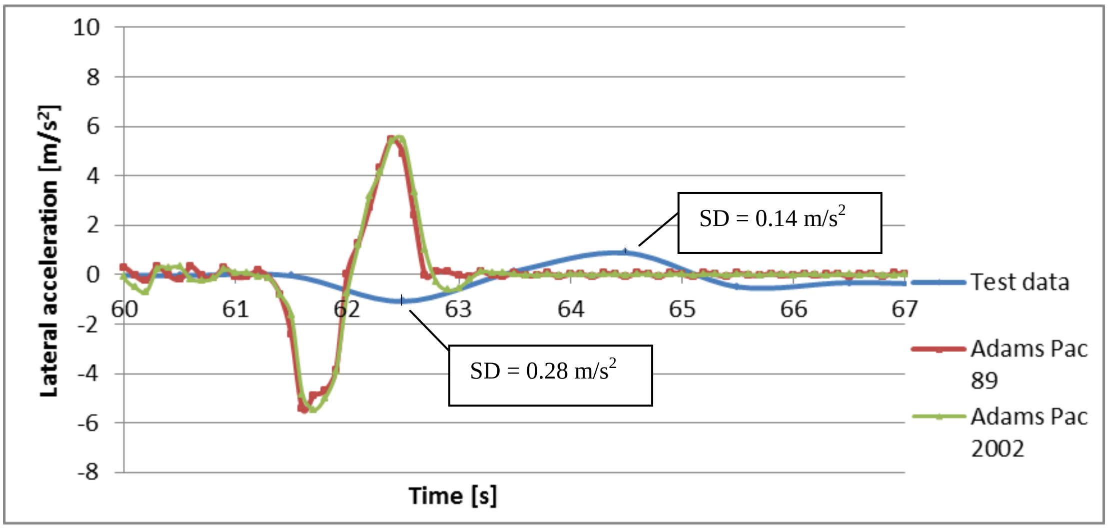

*Figure 6: Lateral acceleration of tyre test rig CG for payload 1 and tyre pressure 1, test speed 1*

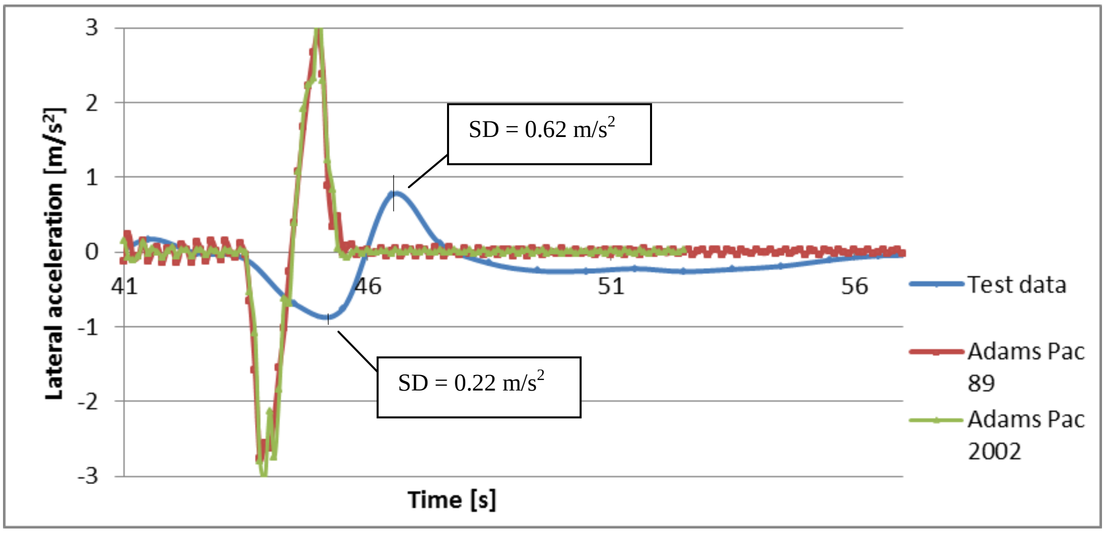

*Figure 7: Lateral acceleration of tyre test rig CG for payload 1 and tyre pressure 1, test speed 2*

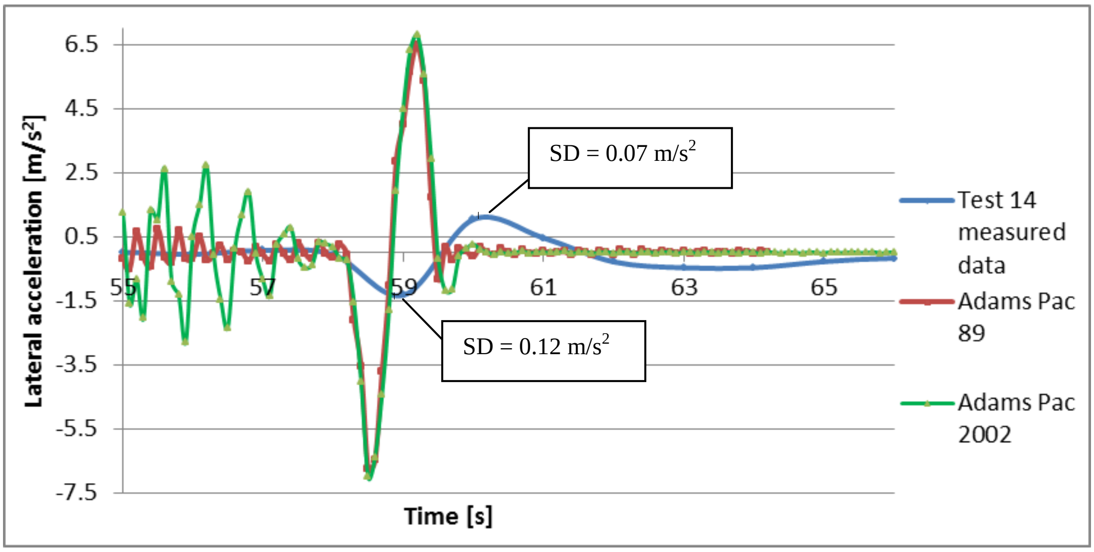

*Figure 8: Lateral acceleration of tyre test rig CG for payload 1 and tyre pressure 1, test speed 3*

From Figures 6 – 8, it can be seen that the computational results differ from the validation test results in amplitude and time response. The results indicate that further investigation is required to determine the reason for the difference between the simulation results and the dynamic lane change validation tests. A sensitivity study on the various parameters that could effect the test rig measurements is to be carried out. It is also proposed that the traditional static method of characterisation, as done in the past (by the original developers of the tyre test rig), may not be correct. That is, it is hypothesised that the error may be because the tyres should be characterised in a continuous dynamic sweep through the various slip angles and should not be characterised by incrementally increasing the slip angle of the tyres before each test run.

### 3.3 Belgian paving vertical dynamics tests

Although more complex, high frequency, tyre models (such as the FTire model and the CDTire model) are better suited for rough terrain or obstacle profiles, it was of interest to determine how the Pacejka 89 and 2002 tyre models compared to physically measured tests on a Belgian paving track.

The tyre loads that were measured during the physical tests were compared to the computational model results using the Pacejka 89 and Pacejka 2002 tyre models mounted on to the test rig. Figures 9 and 10 show, respectively, the measured vertical tyre forces and accelerations (of the CG of the test rig) from tests and simulations.

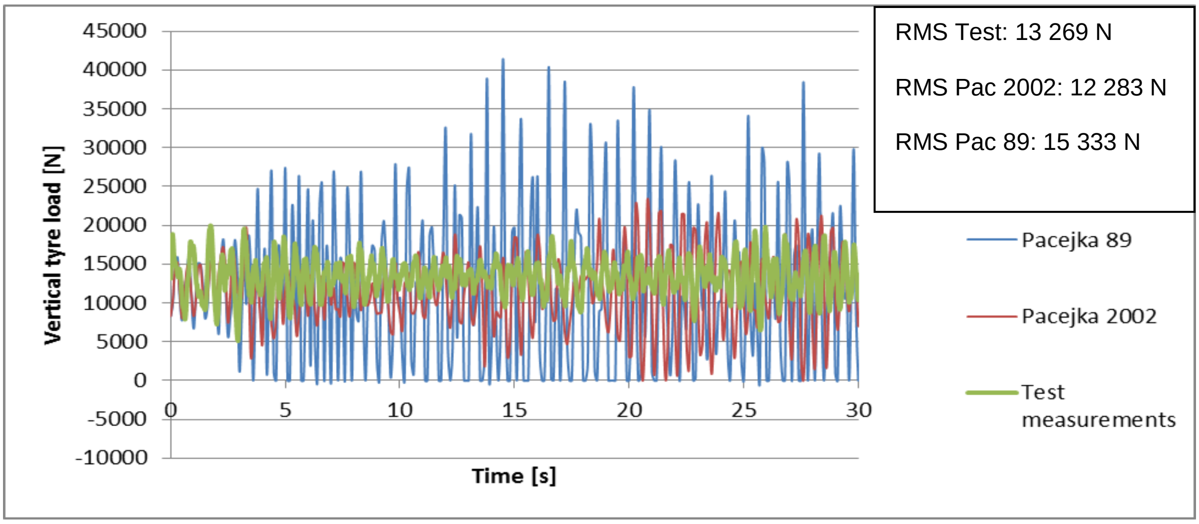

*Figure 9: Belgian paving vertical tyre loads (simulation vs. physical measurement)*

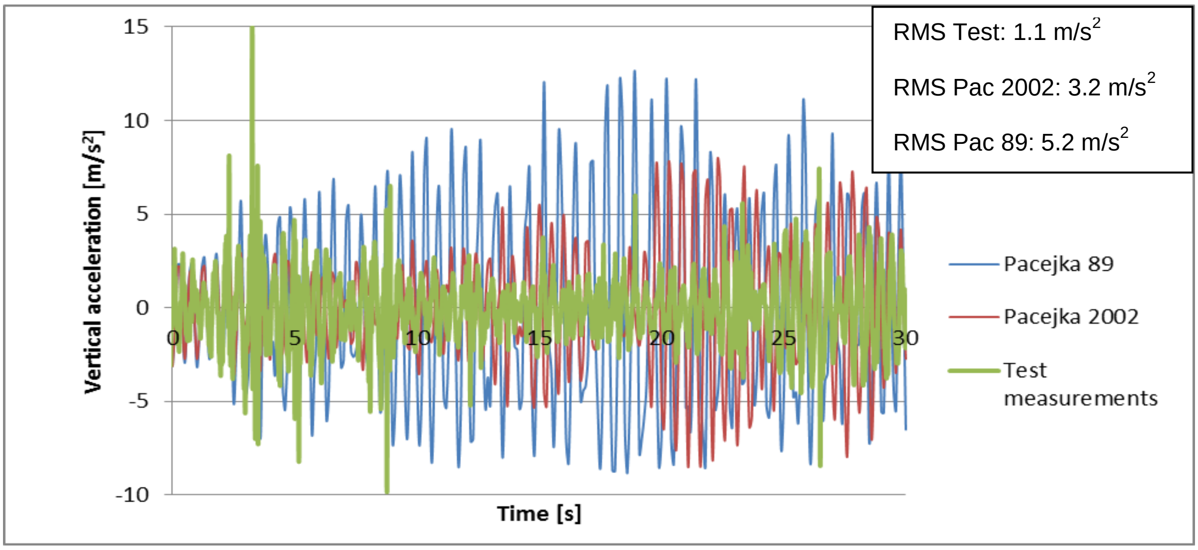

*Figure 10: Belgian paving test rig vertical accelerations (simulation vs. physical measurement)*

Figures 9 and 10 indicate that the Pacejka 2002 tyre model is in closer agreement with the physical test measurements compared to the Pacejka 89 tyre model, although it, sometimes, over-predicts vertical force and vertical acceleration.

Table 1 summarises the root-mean-square (RMS) values of the test rig CG vertical accelerations and vertical tyre forces for the Belgian paving physical tests and computational simulations with Pacejka 2002 tyre models and Pacejka 89 tyre models.

*Table 1: RMS values for test rig CG vertical acceleration and vertical tyre load*

| **5 km/h test speed, 1800 kg payload, tyre pressure 1** | | | |
|---|---|---|---|
| | Physical test | Pacejka 2002 | Pacejka 89 |
| RMS vertical acceleration [m/s$^2$] | 1.1 | 3.2 | 5.2 |
| RMS tyre vertical load [N] | 13269 | 12283 | 15333 |
| **5 km/h test speed, 0 kg payload, tyre pressure 1** | | | |
| | Physical test | Pacejka 2002 | Pacejka 89 |
| RMS vertical acceleration [m/s$^2$] | 4.8 | 6.6 | 7.3 |
| RMS tyre vertical load [N] | 4379 | 4301 | 4863 |

It can be seen, in Table 1, that the Pacejka 2002 tyre model is better in predicting vertical force and acceleration than the Pacejka 89 tyre model, although the vertical acceleration results are not in close agreement with the measured values.

# 4 DISCUSSION

The comparison of the static tyre characterisation tests conducted in order to generate the Pacejka 89 and 2002 MF models and the computational simulations were in reasonable agreement. This indicated that the tyre computational model was generating the same forces that were used to create the model.

In order to validate the computational tyre models, computational and physical lane change tests were conducted with the tyre test rig. Although the Pacejka 89 and Pacejka 2002 models were generated from the characterisation test data by using two independent methods, the resulting dynamics of the simulated lane changes with each tyre model were in good agreement with each other. However, they differed from the physical lane change test data. This indicated that the generated tyre models were not a good representation of the real physical tyre.

Since the Pacejka 89 computational tyre (generated via an in-house script) and the Pacejka 2002 computational tyre (generated using the MSC ADAMS TDFT) behaved the same in the simulations, it was deduced that the method for generating the tyre models from the characterisation test data was not the fault. It was also deduced that, since the static physical and simulation test results were in agreement, that the tyre models represent the physical tyre for static, gradual, slip increments. However, the purpose of a tyre model is to behave the same as the physical tyre in dynamic conditions. This implies that the method of characterising the tyres (by incrementally, and not continuously, increasing the lateral slip angle) may not be correct even though this was the method used in the past.

Based on 14 dynamic lane change validation tests, it is hypothesized that the better method for characterising physical tyres, to generate Pacejka MF computational representations, is to continuously (i.e. dynamically) change the lateral slip angle while the test rig is being towed at a constant velocity. The dynamic forces should improve the models generated by the medium tyre test rig.

The Pacejka 2002 model was a better representation of the physical tyre in the vertical direction than the Pacejka 89 model was, during the Belgian paving physical tests and simulations. Thus, there is potential for using the Pacejka 2002 tyre model for CSIR LS vehicle modelling, within limit.

## 5 CONCLUSIONS

- The Pacejka 89 and Pacejka 2002 computational tyre models generated with the use of the medium tyre test rig represented the physical tyre only in “static” conditions. That is, where the computational tyre lateral slip angle was changed incrementally, at a constant velocity.
- The Pacejka 89 and Pacejka 2002 computational tyre models did not represent the physical tyre in dynamic conditions, such as a lane change manoeuvre. This is probably due to the “static” characterisation method. The method of tyre characterisation should be changed to continuously vary the slip angle.
- The Pacejka 2002 tyre model is better in representing vertical tyre dynamics than the Pacejka 89 model.

## 6 RECOMMENDATIONS

It is recommended that tyre characterisation tests, which were conducted with the medium tyre test rig, be re-conducted with the tyre slip angle being varied continuously. Thereafter, the validation tests should be re-conducted to evaluate whether the tyre models are more accurate.

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