

COMMISSIONING OF THE CSIR'S TYRE TESTING AND STRESS-IN-MOTION FACILITIES FOR IMPROVED TYRE PARAMETERISATION

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ABSTRACT

All of a vehicle's cornering and acceleration forces are transmitted through its tyres to the road. Tyre testing and parameterisation are therefore fundamental to vehicle dynamics research. Lateral stiffness properties are typically acquired using a tyre tester, such as the CSIR's medium-sized trailer-type tyre tester. Other tyre parameters important for road wear impact research include the stress distributions in the tyre contact patch. The CSIR's proprietary Stress-In-Motion system (SIMS) was developed to measure these stresses in three dimensions, primarily for road wear impact research. In this paper, we present the commissioning of both the CSIR's medium tyre tester and the CSIR's SIMS, with the aim of ultimately combining simultaneous measurements from both to provide new levels of tyre parameterisation data. Critical to the commissioning of the trailer itself was verification of the on-board load cells and slip angle adjustment. In addition to this, calibration of the on-board sensors and data acquisition systems was performed. These systems include an inertial measurement unit, a Correvit slip-angle sensor, a camera-based slip angle measurement system, and string potentiometers. Valuable lessons were learnt in the commissioning and integration of all the disparate systems. This prepares the way for future tyre parameterisation research, especially for heavy-duty vehicle tyres.

Keywords: Tyre parameterisation, Slip angle, Stress-in-motion, Vehicle dynamics

1. INTRODUCTION

1.1 Background

Understanding tyre dynamics is crucial for vehicle dynamics research, as every vehicle is connected to the ground through the small tyre contact patches. Through these contact patches, all the cornering, acceleration and braking forces are transmitted to the road (Stainforth 1999).

All of the suspension properties, kinematics and compliance, are downstream of the tyres, and thus accurately characterising a vehicle's tyres is critical to vehicle dynamics research.

This is done by parameterising a mathematic model of a tyre. The model must be able to accurately represent how it develops lateral and longitudinal forces under varying loading conditions. There are many different tyre models with varying degrees of complexity but fundamentally, these models all require some measure of physical test data to be adequately parameterised. Examples of tyre models include Pacejka (89, 94, 2002), Delft-Tyre, CD Tyre, and FTire.

Common to all tyre models is the need for lateral force versus slip angle test data, as a function of vertical tyre load, which is illustrated in Figure 1. The tyre slip angle is distinct from the steering angle and is defined as the angle between the instantaneous heading of the tyre, and the instantaneous direction of motion of the tyre. From this data, a Pacejka 89 model, or 'Magic Formula', can be parameterised (Pacejka 1989).

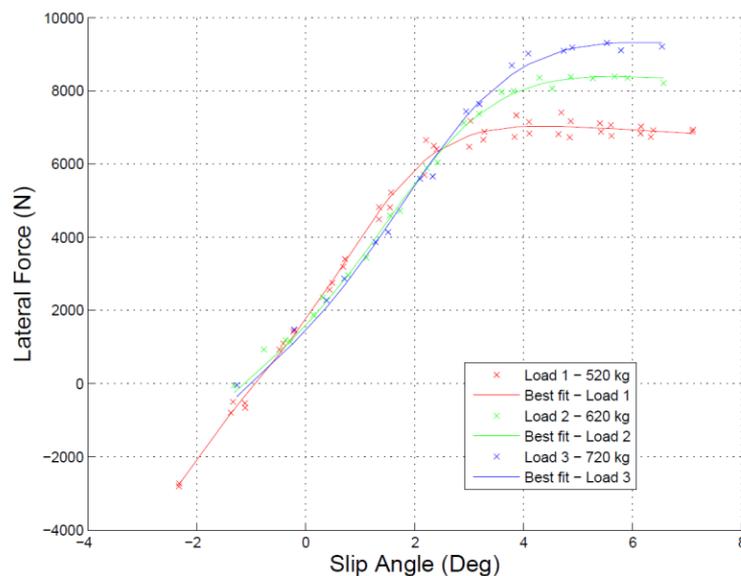


Figure 1: Sample lateral force vs. slip angle curve (Berman 2016)

1.2 The CSIR medium tyre tester

The CSIR's medium tyre tester is a trailer-type tyre tester that requires a tow vehicle and is used to test tyres on the actual surfaces the tyres are used on. This is in contrast with laboratory testing, which is typically carried out on drum-type or belt-type tyre testers. Laboratory testing allows for the testing conditions and environment to be more closely controlled, but do not always represent real road (or off-road) conditions.

The CSIR medium tyre tester, shown in Figure 1, has steering mechanisms for each wheel, which must be set to equal, but opposite steer angles. That is either both toe-in or toe-out, to balance the lateral forces developed by each tyre. The right-hand side wheel is isolated from the trailer body via a sub-frame, which in turn is mounted to the trailer body via six load cells: two lateral, one longitudinal, and three vertical.

The CSIR also has a similar, but larger tyre tester, to test military and commercial heavy vehicle tyres. Both of these can be used to test tyres on and off-road. The CSIR medium tyre tester was originally developed in the 1990s in collaboration with Armscor and the SANDF.

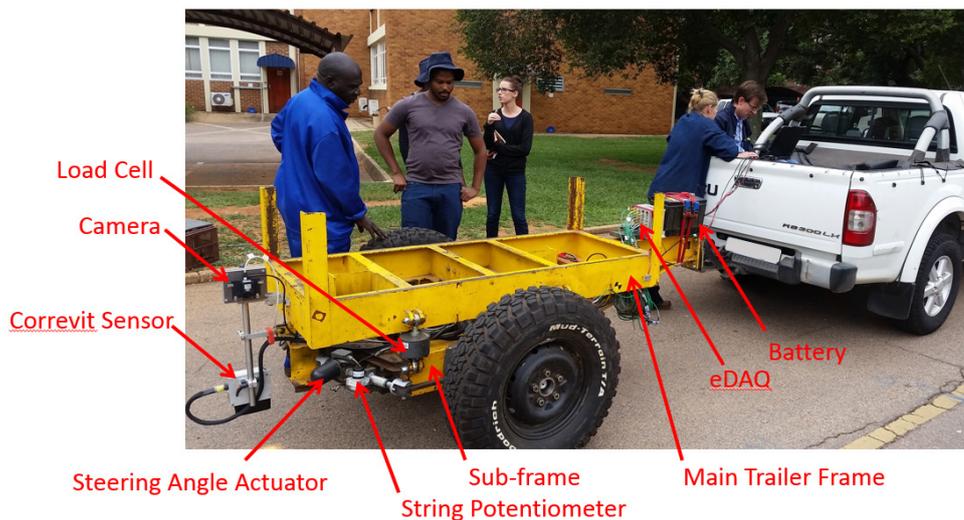


Figure 2: CSIR's medium tyre tester

1.3 Scope of paper

The field tests described in this paper are the first in a series of tests that are planned, and as such, this paper describes the commissioning of the tyre tester, as well as all the ancillary equipment required to conduct the testing. We also present the commissioning of tyre testing in conjunction with the CSIR's Stress-In-Motion system (SIMS). The SIMS system has primarily been used to research the impact of vehicle loads on road wear, but this study forms part of the investigation into the use of the SIMS as a novel tyre parameterisation research tool.

2. METHODOLOGY

The tyres that were to be tested during the recommissioning of the medium tyre tester were BF Goodrich Mud Terrain T/A Km2 tyres. These are commonly-used tyres for on/off-road SUVs.

2.1 Preparation and calibration

The CSIR medium tyre tester was last used in 2013 by Sharma *et al.*, to parameterise a set of multipurpose SUV tyres, and was subsequently placed in storage. Hence there was a need to recommission the trailer, prepare it for testing and recalibrate its sensors.

2.1.1 Load cells

The first step in the recommissioning process was to disassemble the tyre tester and remove the six load cells. The load cells were previously calibrated in tension, but for the recommissioning, they were also calibrated in compression using a load cell with a valid calibration certificate. The load cells were also permanently labelled to ensure the same load cell would always be used in the correct position on the tyre tester.

After the load cells had been calibrated and labelled, they were reinstalled, with extreme care being taken to ensure that the sub-frame was as close to orthogonal to the tyre tester body as possible. This was done by adjusting the rose joints on each load cell.

2.1.2 Steering angle

The steering angle of each wheel must be accurately controlled to ensure that the lateral forces developed during testing are balanced. This could lead to instability or off-tracking

of the trailer which would skew the results or introduce unwanted noise into the force measurement.

The left-and right-hand side steering angles on the tyre tester are controlled by a set of Bircraft linear actuators that attach on one end to the tyre tester frame, and to a steering arm connected to the adjustable hub on the other end, as shown in Figure 3.

The steering angle was measured using string potentiometers attached to each end of the Bircraft linear actuators. The output voltages of the string potentiometers were recorded for a range of steering angles. The steering angles which were calculated by measuring the linear distance between fixed points on the trailer body, and the steering arm. A bar was clamped to the wheel hub, and the lateral distance between the front and rear of the bar was measured (relative to the tyre tester body) for the full range of steering angles.

This process was repeated for both hubs, to obtain a calibration curve for each wheel. During the testing, the slip angle was manually adjusted to ensure the slip angle of both wheels was accurately controlled and maintained equal in magnitude.

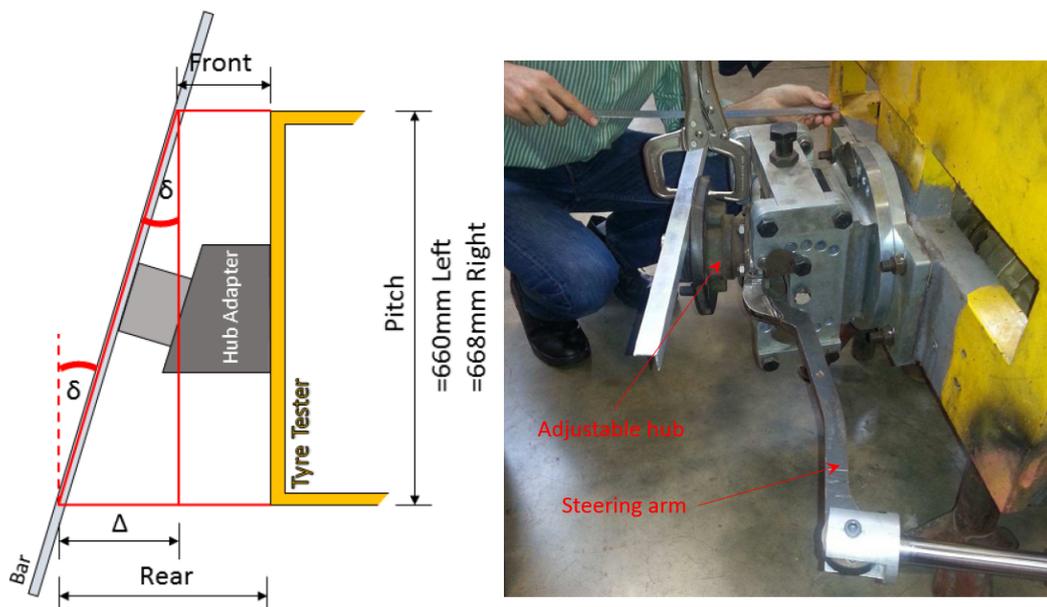


Figure 3: Slip angle calibration schematic

2.2 Components to be fabricated

Before the testing could commence, a set of components needed to be fabricated. The wheel adapters were specific to the wheels and tyres being tested, with the remainder of the component being generic upgrades to the tyre tester.

2.2.1 Wheel adapter

The adjustable hubs on the medium tyre tester have a bolt centre diameter (BCD) that is uncommon on modern off-road tyre rims. As such, it is not possible to mount the rim for the BF Goodrich tyres directly to the hub. A steel wheel adapter was designed and manufactured, with the BCD of the test rim. The six wheel studs were then pressed into the adapter, the adapter was bolted to the rim, shown in Figure 3, and the test rim could then be bolted to the adapter.

2.2.2 Steering actuator bushings

During the steer angle calibration process, it became apparent that the connection between the Bircraft linear actuators and the steering arms contained excessive rotational lash. This lash would cause a sudden step in the slip angle measured by the string potentiometers, but without a change in steering angle. This would not be acceptable during testing and so to eliminate the lash, a set of rubber bushings were fabricated and fitted to each end of the Bircraft actuators, shown in Figure 4.

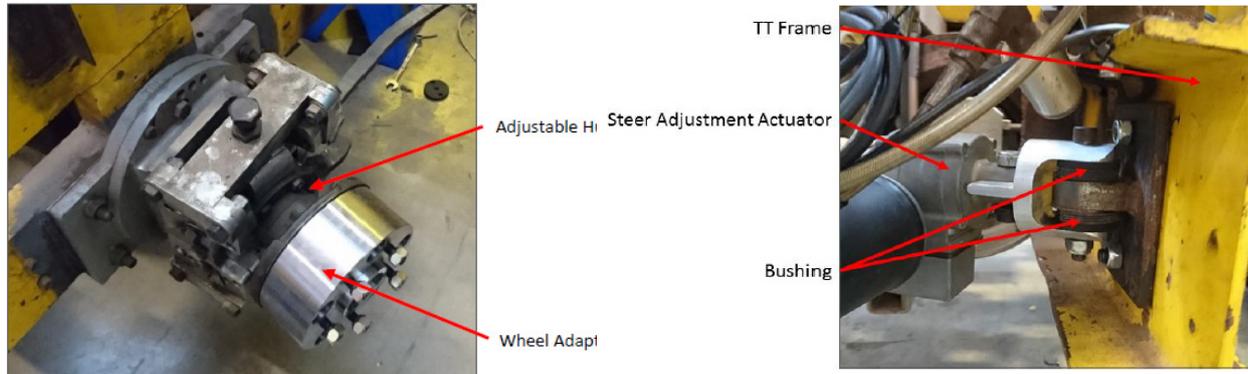


Figure 4: Custom wheel adapter & steering actuator bushings

2.2.3 Correvit sensor and camera bracket

Due to factors such as road surface variations during testing, the forces between the left- and right-hand side tyres are seldom perfectly balanced. This causes the body of the trailer to yaw by a small angle away from a perfect zero heading; this angle is called vehicle slip angle. In order to determine the tyre slip angle, the difference between the set steering angle of the hub (measured by the string potentiometers) and the vehicle slip angle must be used.

A Correvit sensor and a custom developed camera system were used to measure the trailer slip angle. A custom bracket was fabricated to connect the sensors to the rear of the tyre tester, as shown in Figure 5. The bracket consisted of two plates, which would orient the Correvit sensor and the camera in the same plane, to ensure a minimal offset in their measured values. The development and implementation of these systems are dealt with by de Saxe *et al.* (2019), and will not be dealt with further in this paper.



Figure 5: Correvit Sensor and Camera bracket

2.2.4 Drawbar attachment

The previous tow hitch of the trailer was not available, and so a new one was fabricated. The new tow hitch was made to be adjustable so that the tyre tester could be levelled, regardless of the tow vehicle. The new tow hitch is shown in Figure 6.



Figure 6: Adjustable tow hitch

2.2.5 Mass plate

In order to parameterise a tyre model, testing must be conducted with multiple vertical tyre loads. For the purposes of these tests, this was achieved by using a mass plate. Tests were conducted first with tare mass of the tyre tester, and then with the addition of the mass plate. The plate was 25 mm gauge, and two support bars were welded to the plate to restrain it whilst on the tyre tester, shown in Figure 7. The mass of the plate and the two bars were measured, using an overhead gantry crane scale, to be exactly 300 kg.

To ensure that the tyre loads were known during the testing, the loads were measured using the overhead gantry crane scale. The two tyre loads and hitch loads were then verified by weighing the whole tyre tester. This was done both with and without the mass plate.



Figure 7: Mass plate

2.3 Stress-In-Motion System

The CSIR SIMS has been used for research into the impact of heavy vehicle tyres and road infrastructure protection (de Beer 2008). The SIMS has primarily been used to

determine the vertical tyre loads of heavy vehicles, as well as the pressure distribution across the tyre contact patch. This has been used to study the impact of various heavy vehicle tyres at different loads and different inflation pressures on road pavement structures.

The SIMS system has long been used in testing for pavement infrastructure research, but its use in the tyre testing to parameterise a tyre model is novel.

The latest version of the SIMS, version 5b is shown in Figure 8. It comprises an array of 1 020 cylindrical pins, with the centre lateral row (21 pins) instrumented with tri-axis strain gauges. The strain gauges measure vertical, longitudinal, and lateral forces in each pin. This results in 63 channels, recorded at 1 kHz, with an operating range of vehicle speeds from 1 – 120 km/h, vertical loads up to 200 kN and horizontal loads up to 20 kN.



Figure 8: CSIR SIMS version 5b

For the purpose of the tyre testing, the SIMS system force measurement was to be compared to the on-board load cell measurement, to investigate the potential for using the SIMS to assist in tyre parameterisation.

3. FIELD TESTING

3.1 Instrumentation

One of the key components of the commissioning of the tyre tester was to ensure that all of the instrumentation functioned correctly and that all the signals could be recorded and synchronised for post-processing the data.

The data acquisition system used was a SoMat eDAQ Lite, with TCE software. Signals from the six load cells, the two string potentiometers, the Correvit sensor, and the camera shutter signal were fed into the eDAQ and recorded. The video feed from the camera was fed directly into a laptop via a USB3 cable, which also ran the vehicle slip angle processing software. The shutter signal from the camera fed to the eDAQ was used to synchronise the camera feed and all other signals for post-processing of the data. This is fully detailed by de Saxe *et al* (2019).

In addition to these sensors, a MicroStrain® inertial measurement unit (IMU) was used to record tri-axial accelerations of the trailer. The IMU was mounted vertically on the front surface of the tyre tester frame.

3.2 Test procedures

The testing was carried out on a smooth tar section of road at the CSIR. The location was specifically chosen because it is the test site for the CSIR Stress-In-Motion System (SIMS) version 5b. The testing was conducted at constant speeds of approximately 5 km/h, starting on the smooth tar, and then transitioning onto the SIMS section, with the right-hand side test wheel towed over the SIMS array. The series of tests that were carried out are given in Table 1.

Table 1: Summary of Tests

	Slip Angle							
	-4.67°	-5.14°	-3°	0°	3°	6°	9°	12°
Unladen	x		x	x	x	x	x	x
Laden		x	x	x	x	x	x	x

3.3 Data capturing and post-processing

The bulk of the data was recorded by the eDAQ, with the remainder captured directly to the test laptop. All of the channels recorded by the eDAQ were exported to Matlab® and then filtered using an Equiripple low-pass filter with a pass-band frequency of 20 Hz and stop-band frequency of 30 Hz. This was done to remove the high-frequency noise in the load cell recordings. The pseudo steady-state forces were of interest in these tests, and not high-frequency transient forces.

The delay incurred by the filter was accounted for with an appropriate phase shift in the data. The steering angle measurements were relatively noise-free and as such filtered using a five-point moving average.

4. RESULTS

The results from the 9° slip angle, unladen test are presented below.

4.1 Tyre tester measurements

The forces measured by each load cell are shown in Figure 9. There are three vertical, one longitudinal, and two lateral load cells. From the results, it can be seen that there is an event from 11 seconds onwards. This corresponds with the transition from the smooth tar to the SIMS pad. Figure 10 shows the longitudinal and lateral velocities of the trailer, as well as the vehicle slip angle of the trailer.

From both figures, there is a clear change in the vehicle slip angle at the 11-second mark, which corresponds with the entry onto the SIMS. This sudden change in vehicle slip angle was also visually noted during the testing. From Figure 8 above, there is a steel plate placed between the SIMS pad and the tar. This was necessary to bridge the void of the trench the SIMS pad sits in and the SIMS pad itself. The transition from the tar to the steel plate results in a sudden change in friction coefficient on the right-hand side tyre, which causes the trailer to yaw.

This suggests that ideally there should be a mirror image SIMS setup for both the left and right-hand side wheel during these kinds of tests. A previous outdated version of the SIMS pad can be placed in the path of the left trailer wheel to match the conditions of the right wheel. This should significantly reduce the sudden vehicle slip angle of the trailer as it transitions onto the SIMS.

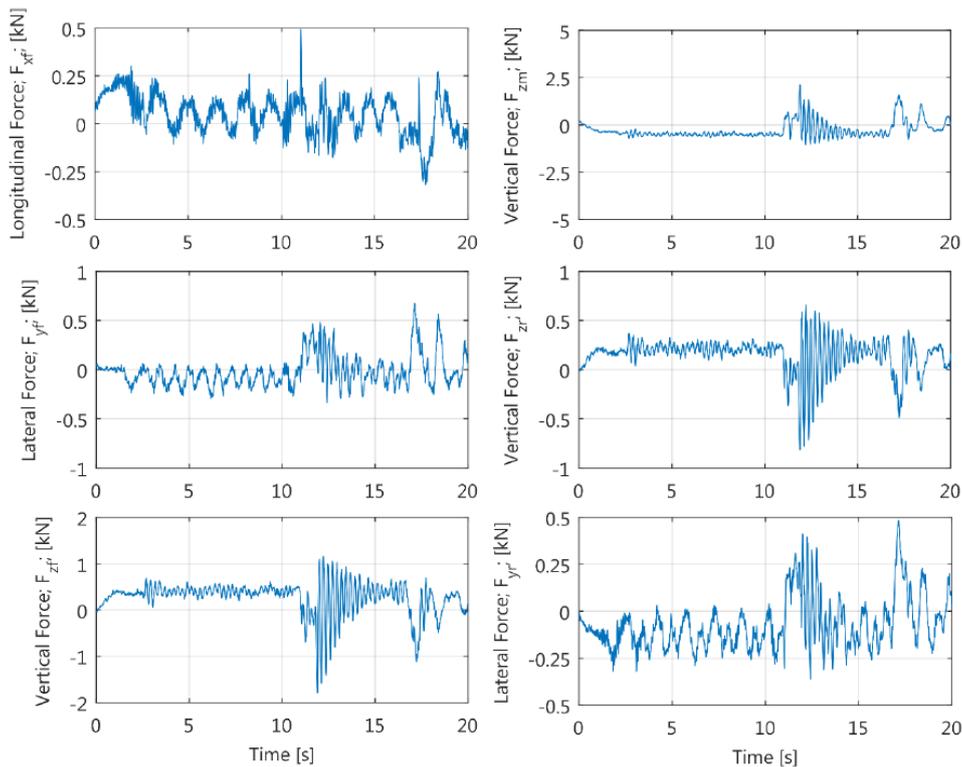


Figure 9: Load cell forces

4.2 SIMS results

The results from the SIMS are shown in Figure 11, given for lateral, longitudinal and vertical stress distributions. The plots show the characteristic stress as a function of lateral and longitudinal coordinates across the contact patch.

The vertical stress distribution plot shows two distinct peaks, one slightly lower than the other. This is to be expected with the large slip angle of 9° , causing a lateral shift in vertical load across the contact patch. This distribution is a typical 'M' type distribution, as described by de Beer (1994).

The longitudinal force distribution closely mirrors the vertical distribution, which is exactly as expected. The wheels on the trailer were free to roll, with no braking or acceleration being applied to the wheels. Slight variations between the distributions can be attributed to partial tread block contact with the pins.

From the lateral stress distribution, it can be seen that there were both positive and negative lateral forces recorded by the SIMS. This is attributed to the large tread blocks on the tyres. It was observed during testing that some of the pins did not even make contact with the tread due to the large gaps. Where there was partial tread block contact, the localised direction of the force could be reversed compared to the net lateral force.

The three pressure distributions not only provide greater insight into the contact patch of a tyre with non-negligible slip angle but also has been shown to be of use in determining the tri-axial forces generated by a tyre with a slip angle.

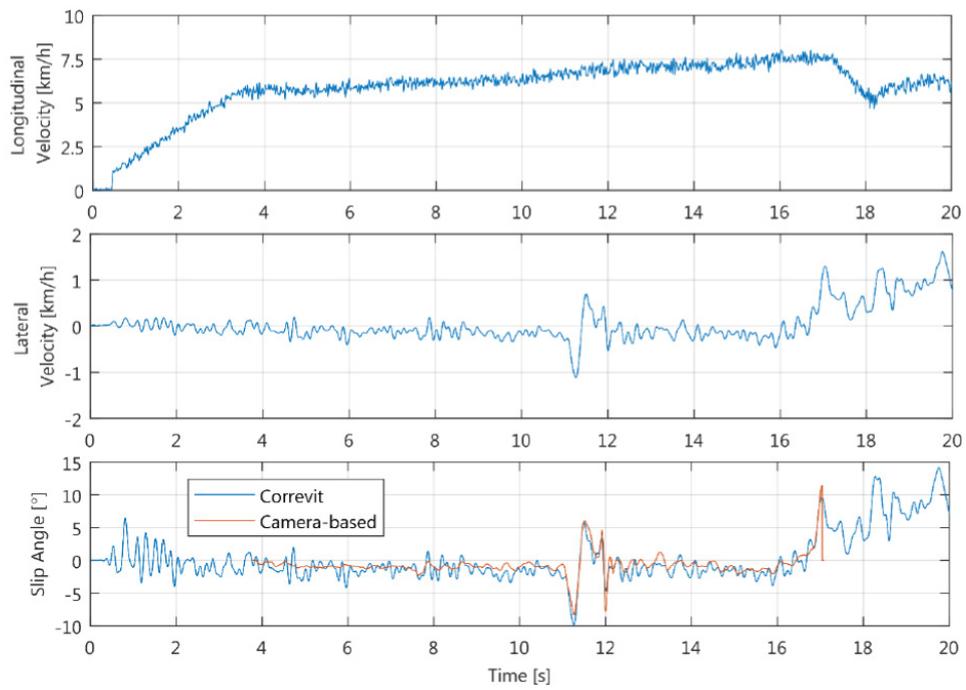


Figure 10: Velocities and vehicle slip angle

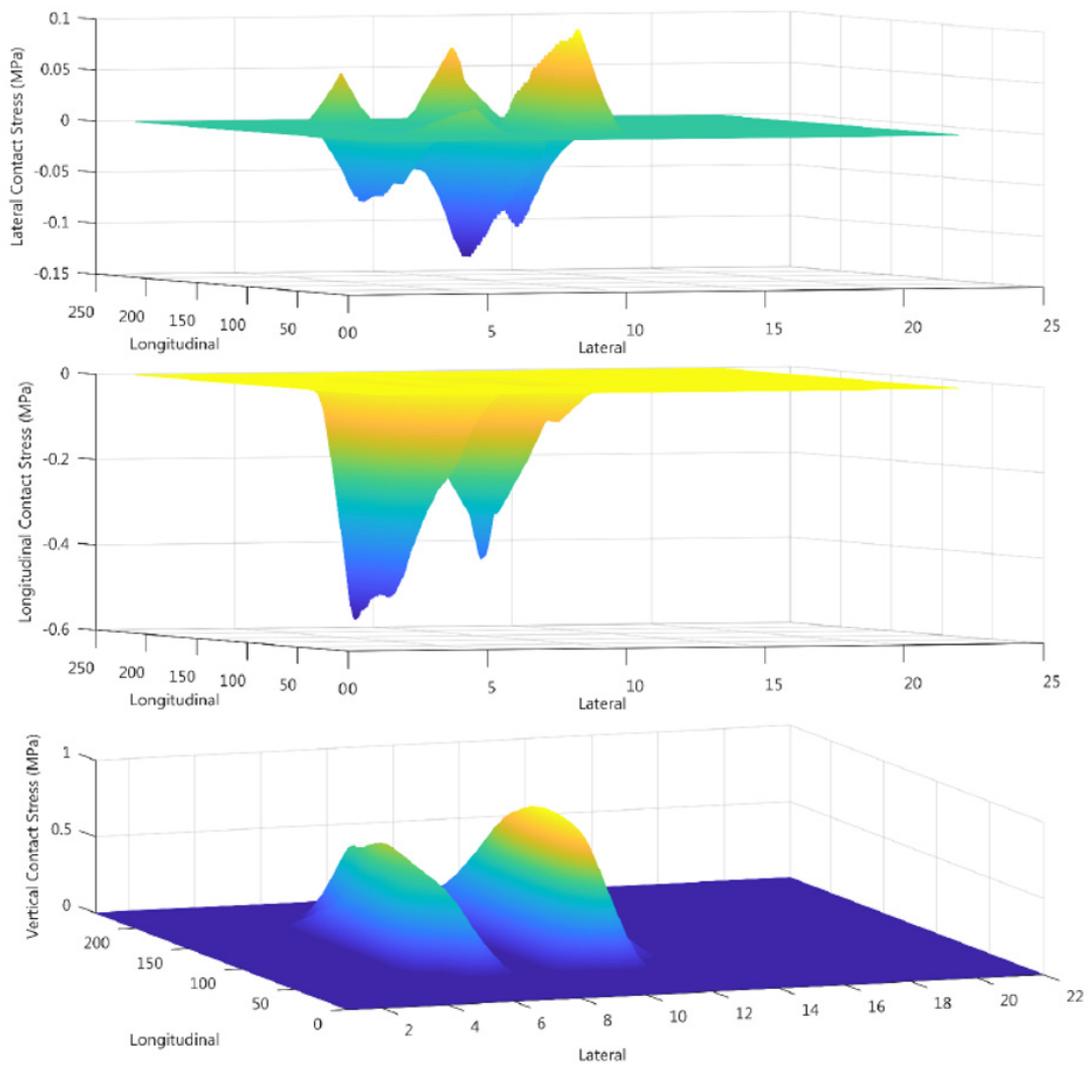


Figure 11: Case 1 SIMS stress distributions

5. CONCLUSIONS AND RECOMMENDATIONS

The CSIR medium tyre tester was brought out of storage and was recommissioned. The first of several planned tests has been described in this paper. The tyre tester was stripped, the load cells were removed and calibrated. During the reassembly of the tyre tester, a number of components were fabricated to improve the control and accuracy of results during testing. A number of custom brackets were also fabricated to allow for new sensors to be mounted and tested during the commissioning testing. A set of tests were conducted, including the novel application of the SIMS in tyre testing to parameterise a tyre model.

It has been demonstrated that the SIMS has potential to be an effective tool for tyre testing to parameterise a tyre model. This is a perfectly reasonable finding, as the SIMS has been used to great effect to study the tyre/road interface downwards. The same forces are transmitted to the vehicle, and can thus be used for vehicle dynamics research.

The main recommendation for the use of the SIMS in tyre testing is to ensure that the exact setup for the right-hand side test wheel is mirrored for the left-hand side wheel. This will include the steel plate and the SIMS pad. Our recommendation is to use a previous decommissioned version of SIMS pad without strain gauges connected, for the left-hand side wheel path. This will replicate the surface for both tyres throughout the entire test and greatly assist in reducing the sudden vehicle slip angle of the trailer as it transitions onto the SIMS.

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