A new efficient free-rolling tyre-testing procedure for the parameterisation of vehicle dynamics tyre models

Smith, G. and Blundell, M.

Original citation & hyperlink:
Smith, G. and Blundell, M. (2016) A new efficient free-rolling tyre-testing procedure for the parameterisation of vehicle dynamics tyre models. Proceedings of the Institution of Mechanical Engineers, Part D: Journal of Automobile Engineering, volume (in press)
http://dx.doi.org/10.1177/0954407016675216

DOI 10.1177/0954407016675216
ISSN 0954-4070
ESSN 2041-2991

Publisher: SAGE

A new efficient free rolling tyre testing procedure for the parameterisation of vehicle dynamics tyre models

G. Smith[1] and M. Blundell[2]

Abstract

This paper describes an efficient tyre test procedure that can be used to gather the data required to parameterise empirical tyre models used in the computer simulation of vehicle dynamics. The new GS2MF FreeRolling test procedure builds on established methodologies, such as the TIME and MICH2MF methods developed as alternatives to traditional square matrix testing. The new process is designed to reduce the number of expensive tyre tests without compromising the accuracy of the generated tyre model parameters.

The process is demonstrated by a programme of tyre testing carried out using the Calspan flat-belt tyre testing facility in the USA and it is shown here how the GS2MF test procedure can be used more efficiently to parameterise the pure lateral and self-aligning moment components for the well-known Magic Formula tyre model. This is achieved using a ‘cruise’ type procedure which is more representative of conditions existing while driving a real vehicle. During the test, a novel automated logic approach is also proposed to manage the tyre temperature. Finally, graph sweeps are introduced at the start and end of the test, allowing a judgement to be made as to the influence of tyre wear on data obtained throughout the test. The development of accurate and representative tyre models remains a significant challenge as vehicle manufacturers target increased use of virtual prototypes and simulation. This work contributes to this challenge by improving the efficiency of the expensive testing process needed to parameterise the models.

Keywords

Tyre testing, GS2MF, free rolling tyre test, tyre modelling, Magic Formula, vehicle dynamics

---

[1]Tyre CAE and Modelling Consultants, Banbury, Oxfordshire, UK
[2]Mobility and Transport Research Centre, Coventry University, U.K.

Corresponding author:
Gregory Smith, Tyre CAE and Modelling Consultants, Lawn Hill Cottage, Appletree, Oxfordshire. OX17 1ET
Email: gregorysmithuk@gmail.com

1. Introduction

The use of computer models and virtual simulation in vehicle development has grown significantly within all areas of the automotive industry. The overall impetus for this is driven by the requirements to reduce cost, improve repeatability and avoid, where possible, the necessity to conduct dangerous manoeuvres at the proving ground. This overall area of activity is recognised as critical in the drive towards the more extended use of virtual prototypes and the ambition to enable total virtual sign-off of new vehicle designs. In some areas the methodologies applied to the modelling of vehicle systems and components are well established. In other areas further development is needed. Of these, the modelling of the pneumatic tyre to support the simulation of vehicle dynamics studies into ride and handling [1, 2] remains one of the most challenging and is the subject of advanced and specialist research. Studies for example into areas such as braking [3] or anti-lock braking systems [4] will require an understanding of the longitudinal force in the tyre as it varies with slip ratio while for vehicle handling studies estimating tyre cornering stiffness [5] and relaxation length [6] are also important.

The appropriate method of modelling a tyre depends on the intended application and can range from large physical models using a finite element approach to represent the tyre structure and materials, to empirical models that represent the forces and moments measured in the tyre contact patch using a tyre test rig. The finite element approach requires detailed and confidential information regarding the tyres material properties and construction; it is therefore best used internally by tyre manufacturers or for specialist research applications [7, 8]. Outside of tyre manufactures semi-empirical tyre models such as FTire [9] and CDTire [10] are often used for ride analysis, while fully empirical models have proven to be the most suitable for simulating handling manoeuvres. A number of researchers have developed handling models to support this; these include the Harty Model [11] and the Fiala model [12]. However, over recent decades the most widely used tyre model is that developed by Pacejka and his associates [13-19]. Originally referred to as the Magic Formula tyre model, this model is now commonly known as the MF-Tyre model and has been developed through many iterations during which time its capability and the number of associated model parameters has been extended. The version of the Magic Formula model that forms the basis of the study presented here is the MF-Tyre 6.1 model, published in 2010 by Besselink et al [20]. The wide ranging capability of the model extends its usage from fundamental vehicle dynamics applications to more advanced studies such as research into anti-lock braking systems and traction control [2].

Before parameterising any empirical tyre model a range of tests must be performed using a tyre test rig to measure the resulting force and moment components generated due to the distribution of pressure and stress in the contact patch. The load cases executed during the test are designed to map the conditions the tyre will see in service for various camber angles, slip angles and values of vertical force. It is also possible to drive or brake the tyre and measure the forces generated due to longitudinal slip.

Complex simulations that aim to map a full range of behaviour involving combined driving or braking with cornering can require an extensive programme of tyre tests to be performed. The rigs used are typically large and expensive laboratory based installations, such as the Calspan flat-belt tyre test rig shown in Figure 1. This facility was used to generate the tyre data presented within this paper.

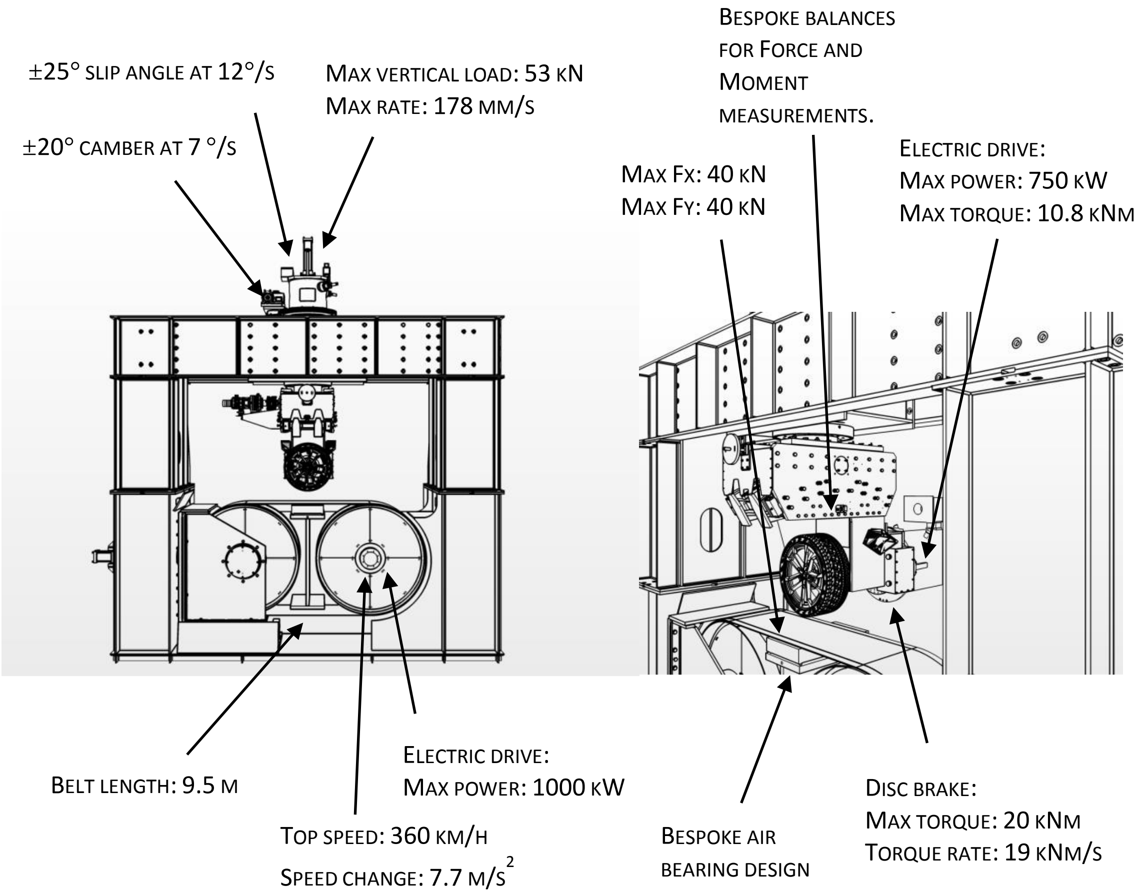


Figure 1. Flat-belt tyre test rig (image courtesy of Calspan Corporation)

Facilities such as this are not common, are expensive and can be considered world class. As such they are fully utilised by automotive manufacturers and research organisations. An overview of tyre testing processes and their use to support tyre modelling in vehicle dynamics can be found in Chapter 13 of [21] and Chapter 5 of [22]. The operational capabilities of the Calspan tyre test rig used here are listed in Table 1.

Characteristic	Range
Slip Angle	-30 deg to +30 deg
Camber Angle	-30 deg to +30 deg
Slip Angle Rate	12 deg/s
Camber Angle Rate	7 deg/s
Tyre Maximum Load	5443 kg
Tyre Load Rate	907 kg/s
Vertical Positioning Rate	178 mm/s
Road Speed	0 to 98 m/s
Tyre Outside Diameter	1194 mm
Tyre Tread Width	607 mm
Belt Width	711 mm

Table 1. Operational capabilities of the Calspan flat-bed tyre test rig [23]

The Magic Formula model has been proven to consistently provide an accurate representation of the tyre behaviour measured on these rigs; however it does require a large parameter set to deliver this accuracy in order to curve fit the model to the measured data. A large parameter set requires a wide range of physical testing to be performed and the cost associated with the extended use of a tyre test facility can become a limiting factor. As such, the focus of the research presented in this paper is to offer a new and efficient methodology that can reduce the number of physical tests performed without compromising the accuracy of the generated Magic Formula parameter set. This new process is referred to as the 'GS2MF FreeRolling test procedure'. Unless otherwise stated all the forces and moments described in this paper are reported using the ISO-W axis system shown in Figure 2.

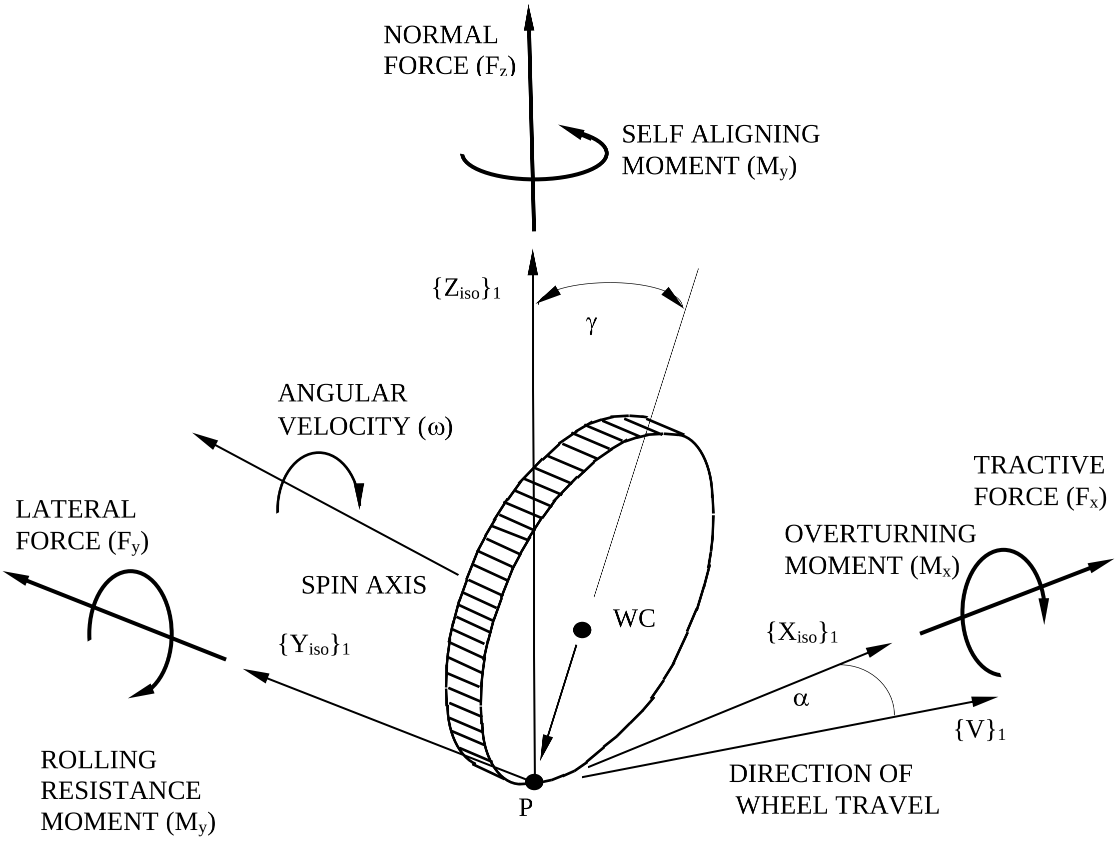


Figure 2. ISO-W tyre axis system

2. Magic Formula

The Magic Formula, or MF-Tyre, model is an empirical tyre model developed for handling based vehicle dynamics modelling. It is designed to replicate force and moment tyre test data for pure lateral cornering, braking, driving and combined handling conditions.

The Magic Formula model was first developed as a joint venture between Volvo Cars and Delft University of Technology [14]. At that time the model was only valid for steady state pure cornering and braking. However, lateral and longitudinal forces as well as self-aligning torque were described accurately. In 1989 the Magic Formula model was updated to include combined cornering and braking, as well as plysteer, conicity and rolling resistance [15]. It was in this paper that the defining form of the Magic Formula as shown in equation (1) was first published.

$$Y(x) = D\sin(C\tan^{-1}(Bx - E(Bx - \tan^{-1}(Bx)))) \tag{1}$$

$$Y(X) = y(x) + S_V$$
$$x = X + S_H$$

In this general form Y(X) stands for either force or moment in the lateral or longitudinal direction and X represents the slip condition. The other parameters include:

B = stiffness factor
C = shape factor
D = peak factor
E = curvature factor
S_V = vertical shift
S_H = horizontal shift

In 1992, Pacejka and Bakker [17] published further updates to the Magic Formula model (now called "Version 3 of the Magic Formula"). Within this version lateral asymmetry was captured, as well as a more accurate representation of camber and accelerating forces. However, the transient response of the tyre was still not included; this wasn't published until 1997 [19], by which time the model was now called "Delft Tyre 97". This version of the Magic Formula model employed concepts of pneumatic trail and residual torque to better model the self-aligning moment. It was also the first time that the relaxation length of the tyre was included in the model.

In 2010, a significant update to the Magic Formula was published [20]. This expanded on the existing versions of the Magic Formula to include inflation pressure scaling such that the tyre model could be set by the end user to any inflation pressure within its tested range. Furthermore, improvements were made to the non-linear transient model and the ability to cope with high camber angles was included for motorcycle applications.

Throughout its development, the various versions of the Magic Formula tyre model have been widely used across the automotive industry as well as in academia for automotive handling applications.

3. Tyre Test Rigs

Magic Formula tyre models are typically built using data obtained using indoor, flat surface test rigs. The first of these was the Tire Research Facility developed by Calspan, Buffalo NY USA and completed in 1973 [24]. It is a highly capable rig engineered to support very high loads and torques; the rig remained fundamentally unchanged from its inception until 2014; when its drive system was upgraded from hydraulic to electric in a bid to increase both power and slip ratio control.

This and other similar rigs such as those built by the MTS Systems Corporation [25] consist of two large drums with a steel belt wrapped around them. This belt is supported between the two drums by an air or water bearing creating a flat, level surface on which to test the tyre. The steel belt is covered with a test surface (typically sandpaper) to simulate a road surface. The test tyre is then mounted to an articulating head above the test surface which allows the tyres' load, slip angle, camber angle and rotational velocity to be controlled; in addition to the speed of the belt and inflation pressure of the tyre; meaning the test can be conducted under a wide range of load cases.

Alternative rigs, such as drum rigs, are less suitable for gathering handling data as they cause the tyres' contact patch to be curved rather than flat; this typically leads to inaccurate lateral force prediction. The need to correct for curvature effects form testing with drum rigs is recognised by the authors in [26] where the use of correction factors is considered when generating parameters for the Magic Formula tyre model. Articulating heads mounted in trailers are often used to gather handling data on public roads, racetracks and proving grounds. This approach can increase accuracy as testing is conducted on real road surfaces rather than sandpaper. However, the repeatability is not to the level of an indoor rig, which can lead to problems when comparing multiple tyres.

4. Existing Test Methods

4.1 Square Matrix

A common method of testing tyres to gather data for the parameterisation of MF-Tyre 6.1 tyre models involves covering a full range of tyre states and is often known as the Square matrix method. This is an approach commonly used in industry to test tyres over a range of input variables including load, camber angle, slip angle and slip ratio. It was described by Blundell [27] although at the time the term Square Matrix was not in common use. It should be noted also that that the method described at that time did not include the procedures that came later to manage tyre temperature and wear during the test programme. For square matrix testing, typically a pair of sweeps is selected when using a square matrix approach to gather low slip angle data at a low rate; followed by high slip angle data at a higher rate. An example of these is shown below:

Low Slip Angle Sweep:	0 → -2 → +15 → -15 → +2 → 0 deg at 4deg/sec
High Slip Angle Sweep:	0 → -5 → +28 → -28 → +5 → 0 deg at 12deg/sec

Additionally, a set of load cases are selected covering a range of constant loads, camber angles and inflation pressures. An example of these values for a 255/55R20 SUV road vehicle tyre is shown below:

Four loads:	3480 N	6960 N	8700 N	10440 N
Three camber angles:	0 deg	-5 deg	5 deg	
Three inflation pressures:	2.1 bar	2.6 bar	3.2 bar	

The low slip angle sweep and the high slip angle sweep are then conducted at every possible combination of load, camber and inflation pressure. This generates a full square matrix data set totalling 72 (four loads × three camber angles × three inflation pressures × two sweep types = 72) individual sweeps.

Due to the effect of excessive tyre wear these 72 sweeps cannot all be conducted on the same tyre, instead six tyre specimens are used. Typically a new tyre will be used for each sweep type and each inflation pressure. This means 12 Low Slip Angle Sweeps are conducted on the same tyre specimen, one sweep at every combination of load and camber angle whilst all at one inflation pressure. A new tyre will then be used for each of the remaining pressures (using three tyres). This is then repeated for the high slip angle sweeps, meaning six tyres are used in total.

The approach is simple and gathers the necessary data to parameterise the MF-Tyre 6.1 tyre models; however, gathering a complete dataset following this method takes approximately 2.8 hours of rig time, making it less cost effective. Furthermore, for vehicle dynamics applications it is very inefficient. Testing symmetrically across all sweeps means data is gathered under load cases unobtainable in a real car. Moreover, if an additional load case is required, such as testing at an additional load; every camber and inflation pressure sweep needs to be conducted at this extra load; whereas in practice only some of the sweeps may be required. Finally, the test procedure assumes all the load cases are equally important but in fact it may be beneficial to gather additional data in more important areas, such as close to zero slip where additional cornering stiffness data can be used to increase the accuracy of the model in this region.

4.2 The TIME test procedure

First published in 1999 by Van Oosten et. al. [28], the TIME project was a collaboration of 14 partners aiming to develop a common tyre measurement procedure in order to make data from various sources more comparable. This was a very extensive study including comparing data from six different tyres tested on 11 different tyre test rigs. It also proposed the idea of a ‘cruising’ type test where the tyre is rolling while subjected to load conditions in a similar fashion to a real vehicle.

This test procedure includes three key sections: a warm up, to heat the tyre into a temperature state closer to its standard operating conditions; a linear sequence, to gather cornering stiffness data at small slip and camber angles; and a non-linear section to gather tyre force and moment data at larger slip conditions.

The particular load cases used in the TIME test procedure are based on the tyres load rating which is a valid way of directly adapting the test procedure to suit the tyre being tested.

The main limitations of the TIME test procedure are that it was developed for earlier versions of the Magic Formula which were used for the procedures’ validation. Hence it does not include any testing to capture the effect of changing inflation pressure which was introduced later in MF-Tyre 6.1. Additionally, the procedure is steady state only and does not include any attempt to capture the tyre transient response.

4.3 The MICH2MF test procedure

The MICH2MF tyre testing procedure was developed by Buisson at the Michelin Tyre Company in France [29]. It is a test procedure which aims to advance on the TIME procedure to ensure the tyres’ thermo-mechanical behaviour is consistent with real driving conditions.

In this paper the author points out that current mathematical models do not capture the effect of tyre temperature and that a tyres’ performance is dependent on its history. With both cornering stiffness and grip characteristics being temperature dependant and the tyre temperature depending on its preceding load conditions; it is important for a test procedure to be as close as possible to the load cases placed on a tyre by a real vehicle when driving. Based on this, the load cases used in the MICH2MF test procedure are calculated using both the size and load rating of the tyre being tested;

as well as the average load conditions observed by driving vehicles on the Michelin Ladoux ‘number three handling track’.

The procedure also includes repeated testing at three different inflation pressures to enable pressure interpolation. However, the latter section of the test needs to be repeated at each pressure, which is inefficient.

The MICH2MF procedure clearly builds on the ‘cruise’ type of testing presented in the TIME procedure and develops the idea further by linking the load cases directly to the loads exerted on the tyre by a real vehicle. This is a sensible idea and means the tyre is tested in a scenario much closer to its intended running conditions. This idea of managing temperature is also sensible when it is not captured in the tyre model.

4.4 Test procedures summary

Based on analysing the existing test procedures the following observations were made:

- Square matrix testing is highly inefficient, using significantly more rig time and tyre specimens than are necessary.
- The TIME and MICH2MF procedures show an alternative ‘cruise’ type test procedure can be much more efficient than square matrix testing.
- The cruise type test procedure can also be more similar to the load cases exerted on a tyre when fitted to a vehicle.
- The TIME and MICH2MF procedures are developed for the MF-Tyre 5.2 tyre models and hence do not including testing at multiple inflation pressures. Therefore, the entire test procedure needs to be repeated at each pressure which loses efficiency.
- The TIME and MICH2MF procedures shows that test loads can be linked directly to the tyres’ load rating.
- The MICH2MF procedure highlights that the tyre performance is dependent on its test history meaning the temperature of the tyre needs to be managed throughout the test procedure.
- None of the test procedures include an integrated section of testing to gather data pertaining to the tyres’ relaxation length.
- In both the TIME and MICH2MF procedures testing is symmetrical which means the tyre is being testing at load cases that are unobtainable in a car.

To address these limitations the GS2MF FreeRolling test procedure has been developed and is described in the next section of this paper.

5. The GS2MF FreeRolling test procedure

The overall GS2MF FreeRolling test procedure requires one tyre specimen and is a single test sequence split into nine distinct sections as shown in Figure 3; the procedure involved in each of these steps can be summarised as:

1. Warmup. The warmup section heats the tyre closer to its operating temperature.
2. Step Steer. Step steer tests are performed to gather data pertaining to the tyres’ relaxation length under various load cases.
3. Graph Sweep 1.Graph sweep 1 is conducted to establish the tyres’ benchmark performance under optimal conditions (warm but only lightly worn).
4. Cornering Stiffness and Vertical Stiffness. Cornering stiffness and vertical stiffness testing is conducted.

5. Force and Moment, Inflation Pressure 1. Force and moment testing is conducted at the lowest inflation pressure.
6. Force and Moment, Inflation Pressure 2. Further force and moment testing is conducted at the middle inflation pressure with a few additional sweeps.
7. Force and Moment, Inflation Pressure 3. Force and moment testing is conducted at the highest pressures, this is identical to the force and moment testing at the lowest pressure.
8. Graph Sweep 2. Graph sweep 2 is a repeat of graph sweep 1; this allows data from these to be compared and the effect of tyre wear to be observed.
9. Severe. Severe testing under high slip angles and cambers is conducted at the end so that the additional wear caused by these sweeps does not affect any other testing.

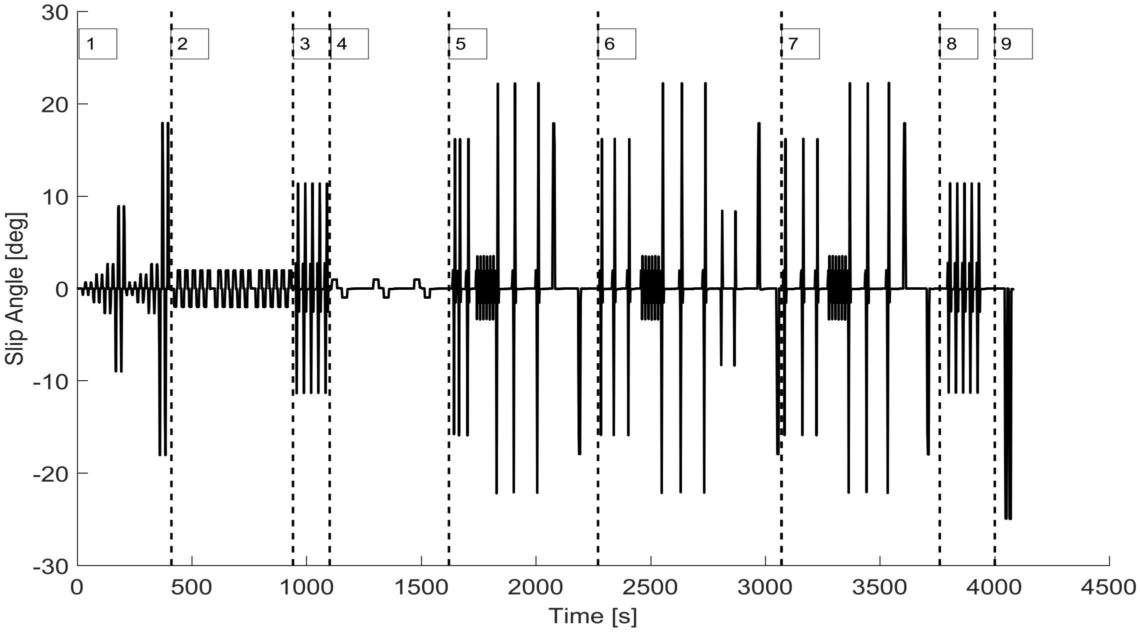


Figure 3. The GS2MF FreeRolling test procedure divided into nine distinct sections.

5.1 Vehicle Weight Transfer with Slip Angle

At an early stage in developing this new procedure vehicle dynamics analysis was conducted using a virtual vehicle simulation to look at the weight transfer of a vehicle and link this to the tyres' slip angles. The slip angles and loads within the GS2MF FreeRolling test procedure were then determined so as to reflect this vehicle behaviour. The GS2MF FreeRolling procedure was then compared to the square matrix test procedure as shown in Figure 4.

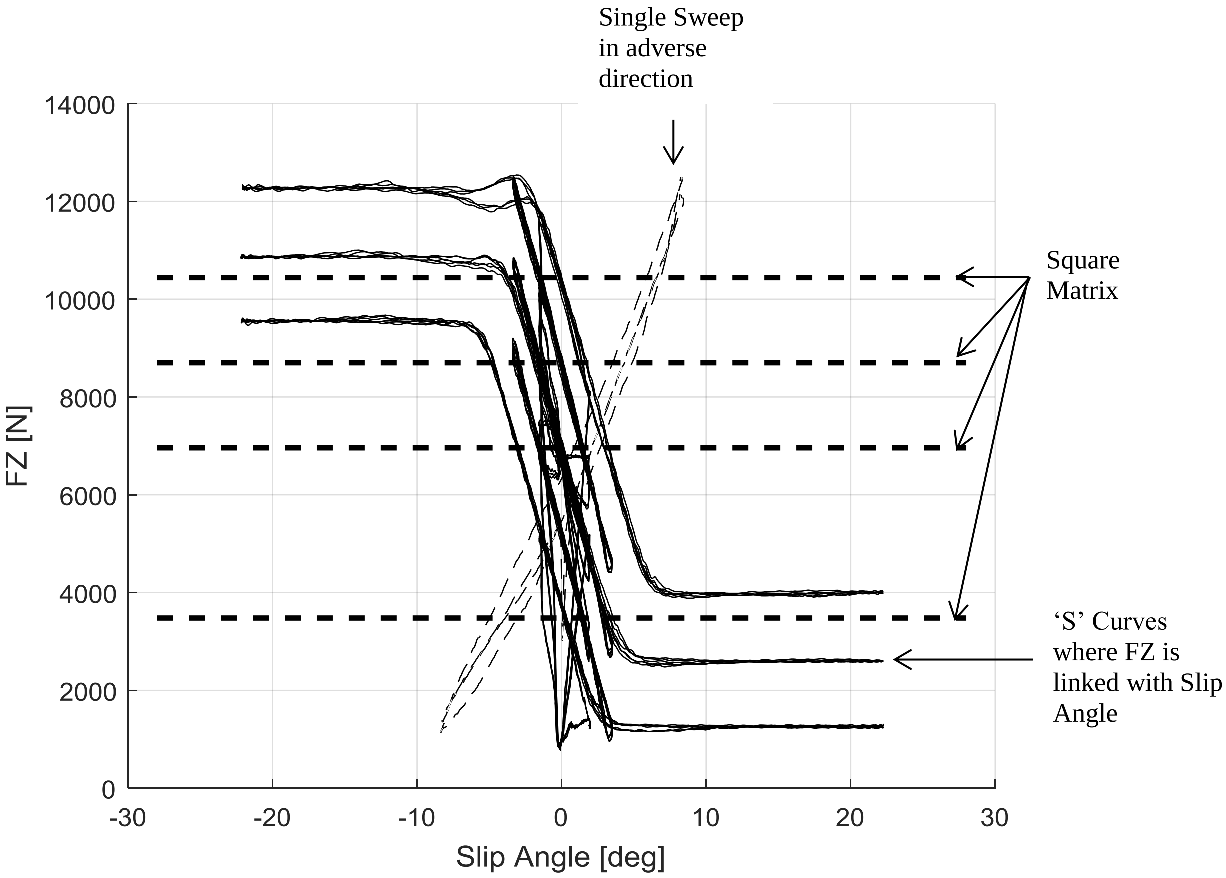


Figure 4. Vertical load linked with slip angle for the GS2MF FreeRolling test procedure overlaid with the square matrix method.

When considering a vehicle's right side tyre the load increases from the static load when steering to the left, and decreases when steering to the right; this is due to the weight transfer of the vehicle during cornering. This weight transfer is not taken into account in the square matrix test procedure. Instead the tyre is being tested under load cases it will never experience on a real vehicle.

For this reason asymmetry was introduced to the GS2MF FreeRolling test procedure where the tyre is only tested with load cases obtainable on a real vehicle. This is shown with the 'S' curves in Figure 4. It can also be seen that these 'S' curves flatten out at a certain slip angle. This represents the point during the vehicle manoeuvre where the tyres are generating peak lateral force, so that the lateral acceleration is constant and hence no further weight transfer can occur. Instead, additional slip angle can be applied but the vertical load remains constant as the tyres have reached a state beyond the point of generating peak lateral force.

5.2 Sweep Shape - Shark Tooth

A compromise exists regarding the slip angle rate used during free rolling cornering tests. If a high slip angle rate is used, the tyre cannot be considered to be in a steady state condition. Due to this mechanical hysteresis is observed, particularly in the linear region close to zero slip angles. This mechanical hysteresis causes a wide spread in the lateral force data when steering out compared to steering in, which makes the fitting of a steady state Magic Formula tyre model less accurate, this is further discussed in section 5.9 on parameterisation. To that end the hysteresis can be reduced by using a slower slip angle rate. However, this causes the tyre to spend more time at large slip angles which increases the tyre's temperature leading to thermal hysteresis. This is where the tyre's force outputs change as a result of the temperature variation across the steering sweep being too high. Furthermore, any additional heating of the tyre means the cool down periods between each sweep need to be longer to allow the heat to dissipate and the tyre to cool to a consistent baseline temperature before starting the next sweep. This then leads to a longer overall test duration and therefore additional test rig costs. A key objective of the GS2MF FreeRolling test procedure is to minimise temperature throughout the test without compromising the data integrity in order to reduce thermal hysteresis and overall test duration.

To address this requirement a variable rate sweep is used, whereby the tyre is steered at a low slip angle rate when close to zero and a higher rate when at high slip angles. A comparison between a variable and constant rate sweep is shown in Figure 5.

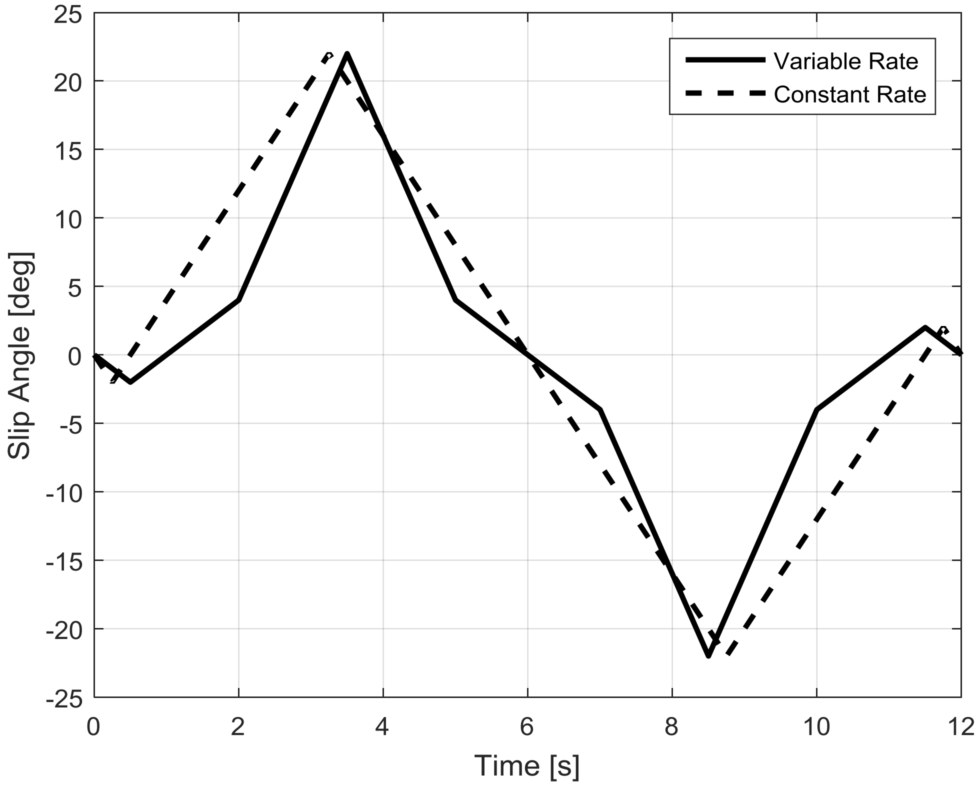
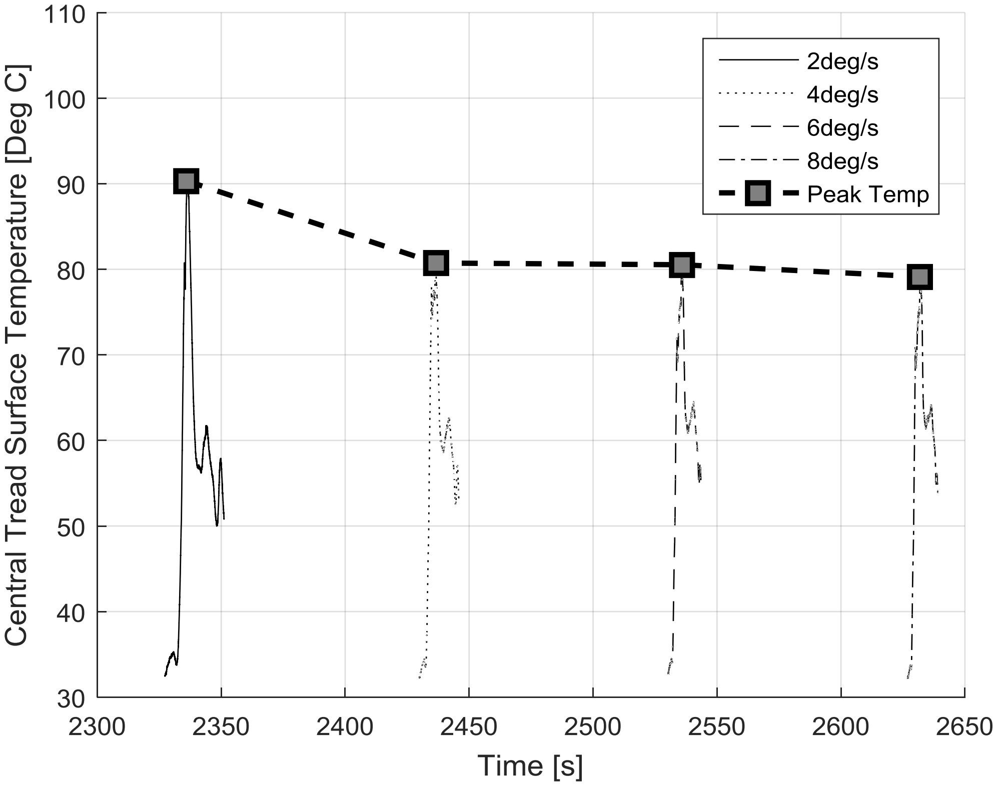


Figure 5. Variable rate versus constant rate sweep; showing that at any given time the variable rate sweep is usually at a lower slip angle than the constant rate sweep; this contributes to less heating of the tyre.

Testing was conducted to validate the variable slip angle rate approach and investigate the optimal low and high slip angle rates as well as the threshold to change between them.

Initially, testing was conducted to select the optimal low slip angle rate. Figure 6 shows the temperature against time results (Figure 6a) and lateral force against slip angle (Figure 6b) for four constant slip angle rate sweeps conducted at 2, 4, 6 and 8 deg/s. The lateral force plot shows that the slowest (2 deg/s) slip rate generated the least mechanical hysteresis, with a variance of +50 to -425 N between steering out and steering in. The average between these being -188 N crossing 0 slip angle, this is the closest to a steady state. The mechanical hysteresis during the 4 deg/s sweep was wider at +365 to – 711 N however the average of -173 N remained similar to the 2 deg/s sweep. The data at 6 and 8 deg/s showed considerably worse mechanical hysteresis and were therefore ruled out. Additionally, the data at 4 deg/s was less noisy and the peak tyre temperature was around 10 °C cooler compared to 2 deg/s. For these reasons a low slip angle rate of 4 deg/s was selected.



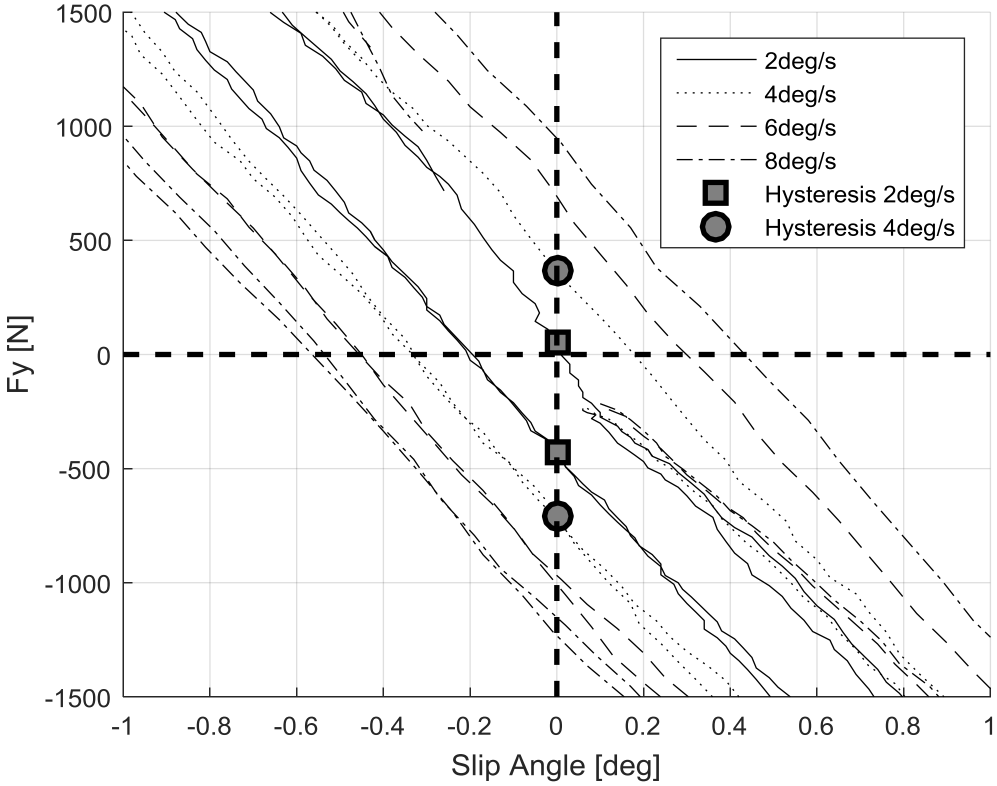
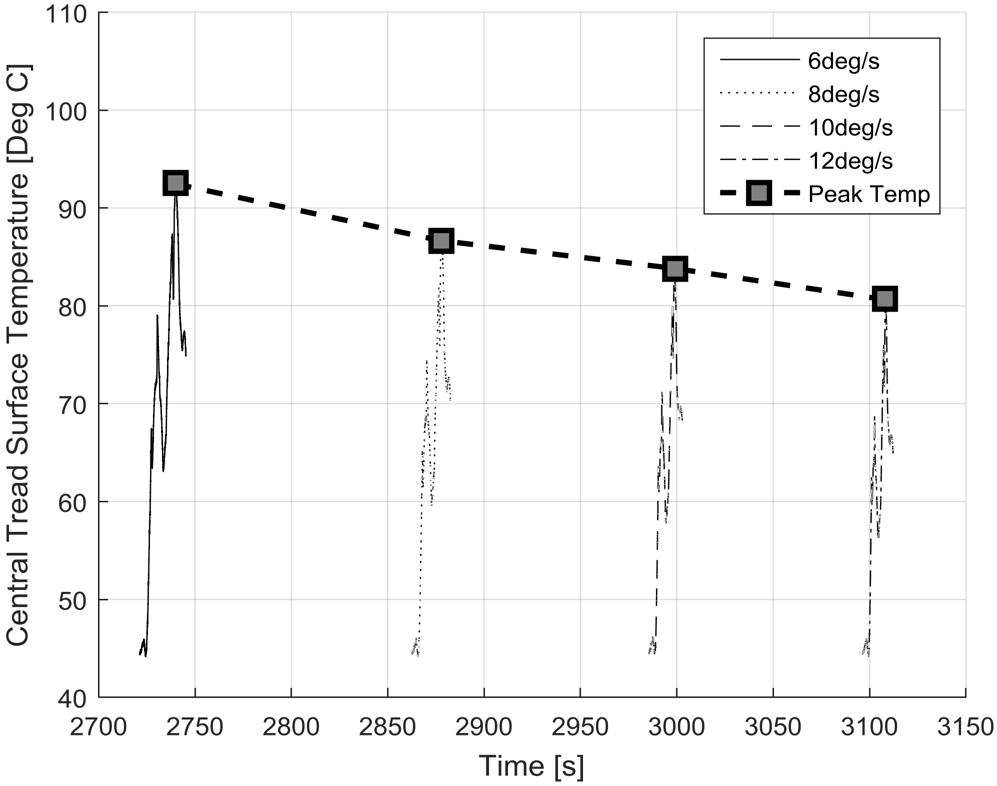
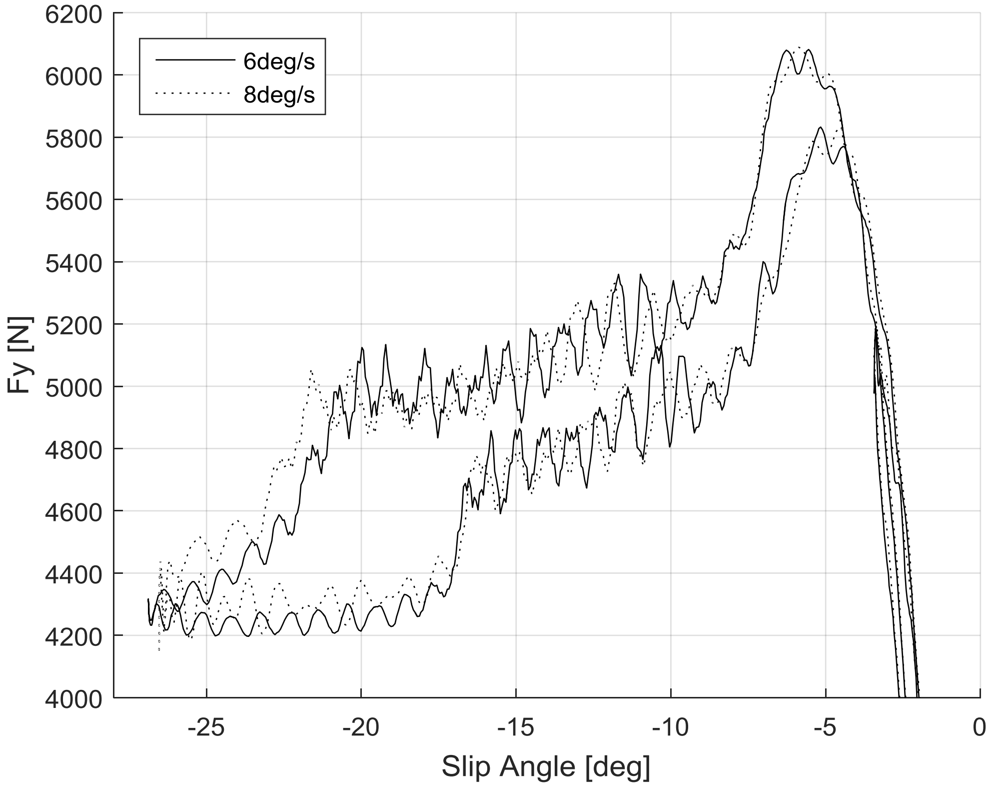


Figure 6a and 6b. The influence of the low speed slip angle rate on the variable rate sweep. The influence on temperature is shown in (Figure 6a - top) and the influence on mechanical hysteresis is shown in (Figure 6b - bottom).

Further testing was conducted to investigate the optimal slip angle rate to be used at high slip angles. Four sweeps were conducted at 6, 8, 10 and 12 deg/s with the lateral force against slip angle, as well as temperature against time results for the four slip angle sweeps shown in Figure 7. The lateral force plot (Figure 7b) shows that the thermal hysteresis is similar across all slip rates. The temperature plot (Figure 7a) shows that the tyre temperature was cooler and more consistent during the fastest (12 deg/s) sweep. For this reason the highest slip rate of 12 deg/s was selected. Testing at higher slip rates would be beneficial however this is the highest slip rate the test rig is capable of.


Central Tread Surface Temperature [Deg C]
Time [s]
6deg/s
8deg/s
10deg/s
12deg/s
Peak Temp
40
50
60
70
80
90
100
110
2700
2750
2800
2850
2900
2950
3000
3050
3100
3150


Fy [N]
Slip Angle [deg]
6deg/s
8deg/s
4000
4200
4400
4600
4800
5000
5200
5400
5600
5800
6000
6200
-25
-20
-15
-10
-5
0

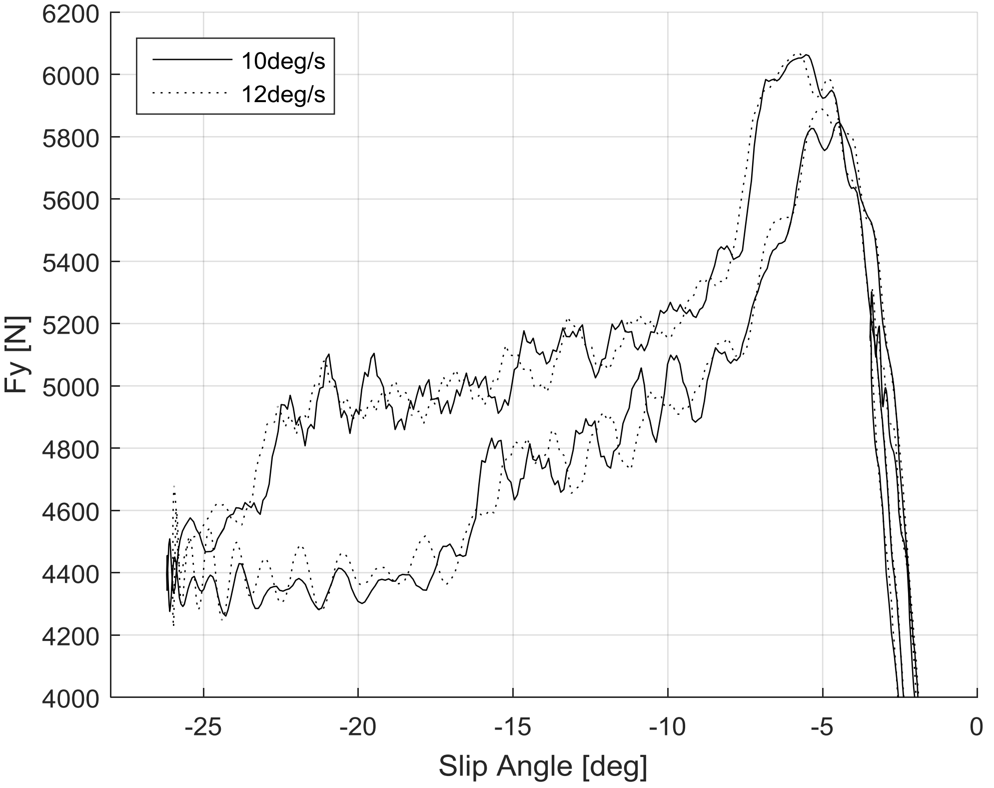
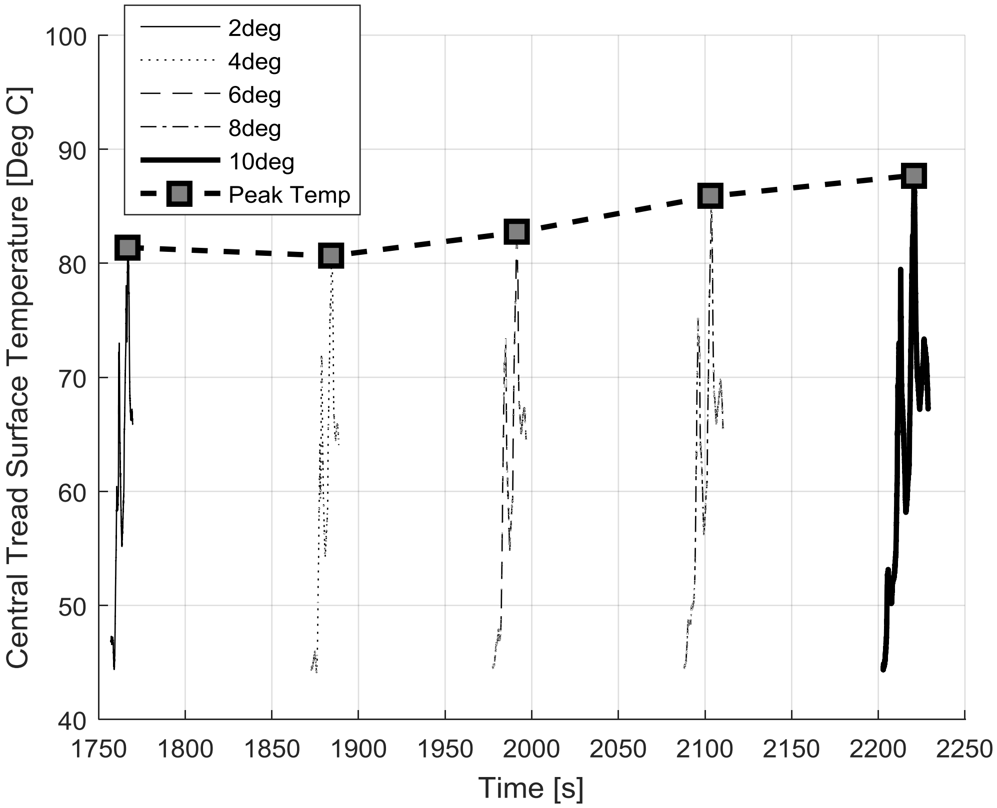
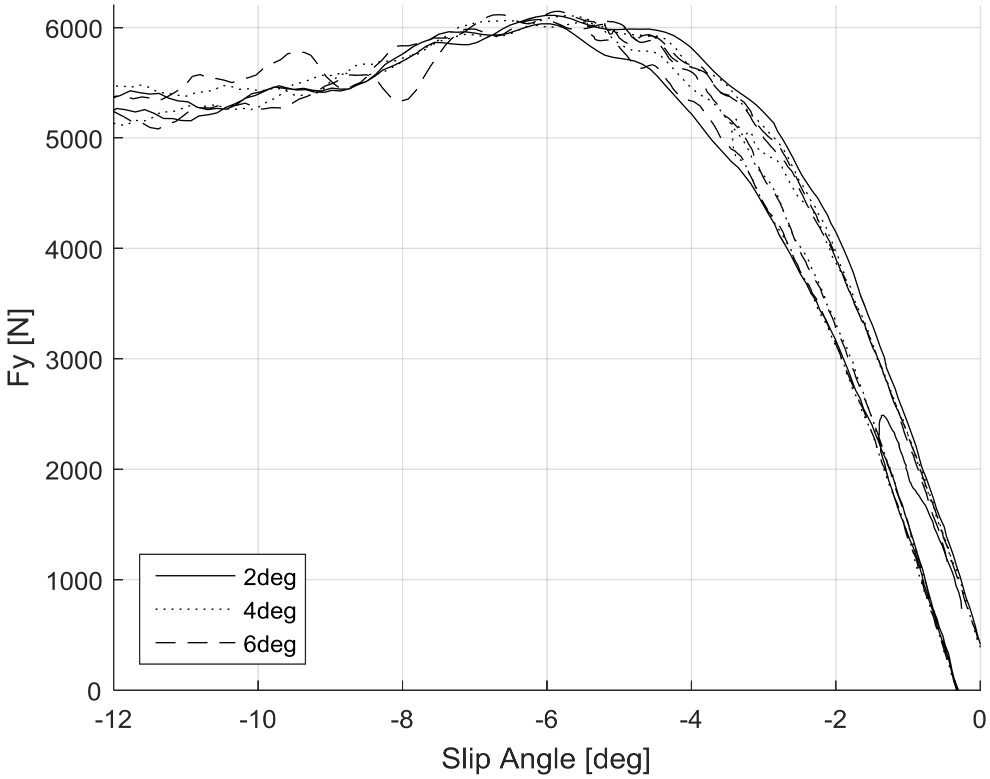


Figure 7a, 7b and 7c. The influence of the high speed slip angle rate on the variable rate sweep. The influence on temperature is shown in Figure 7a – top and the influence on thermal hysteresis is shown in Figure 7b - middle and Figure 7c - bottom.

Finally, additional testing was conducted to determine the optimal slip angle threshold to switch between the low and high slip angle rates. Thresholds of 2, 4, 6, 8 and 10 degrees were investigated and the results shown in Figure 8. The results show there is little change in temperature between the different thresholds (Figure 8a); the lateral force versus slip angle plot (Figure 8b) also shows very little variation. A low threshold is desirable as this results in more time being spent using the high slip rate, which leads to lower sweep times as well as lower overall test time and cost. However, it was decided that the 2 degrees threshold didn’t include sufficient low slip rate data to obtain a reliable cornering stiffness over a wide enough range. For this reason the 4 degrees threshold was selected.


2deg
4deg
6deg
8deg
10deg
Peak Temp
Central Tread Surface Temperature [Deg C]
100
90
80
70
60
50
40
1750
1800
1850
1900
1950
2000
2050
2100
2150
2200
2250
Time [s]


6000
5000
4000
3000
2000
1000
0
Fy [N]
2deg
4deg
6deg
-12
-10
-8
-6
-4
-2
0
Slip Angle [deg]

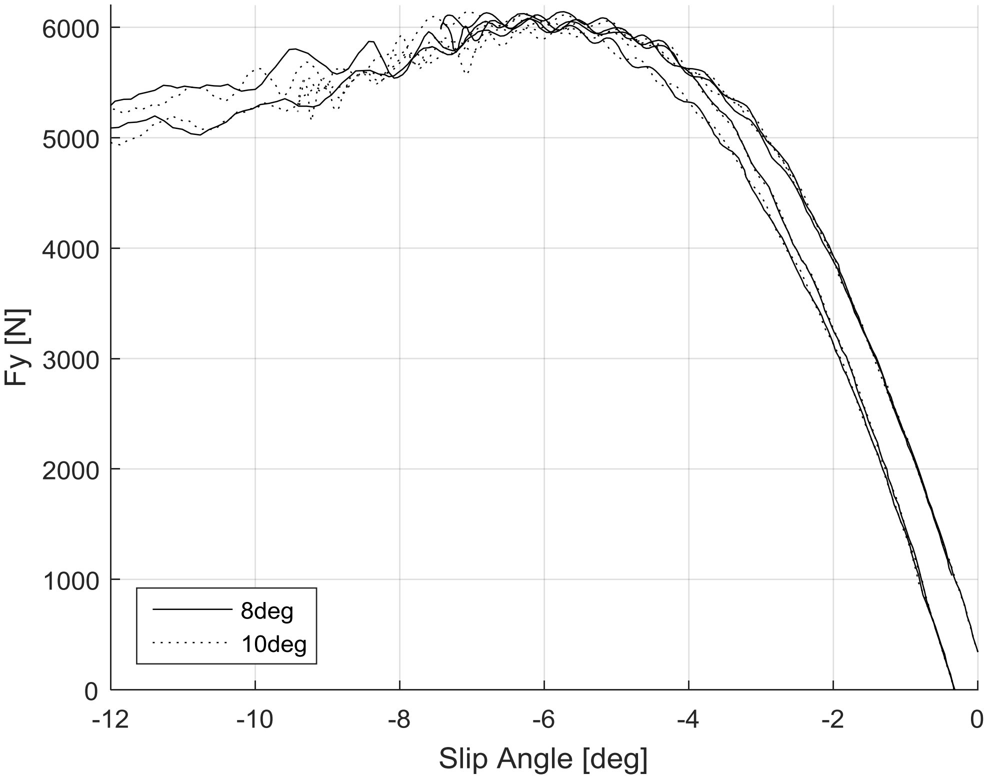


Figure 8a, 8b and 8c. The influence of the high low speed threshold on the variable rate sweep. The Influence on temperature is shown in Figure 8a – top and the influence on thermal hysteresis is shown in Figure 8b – middle and Figure 8c - bottom

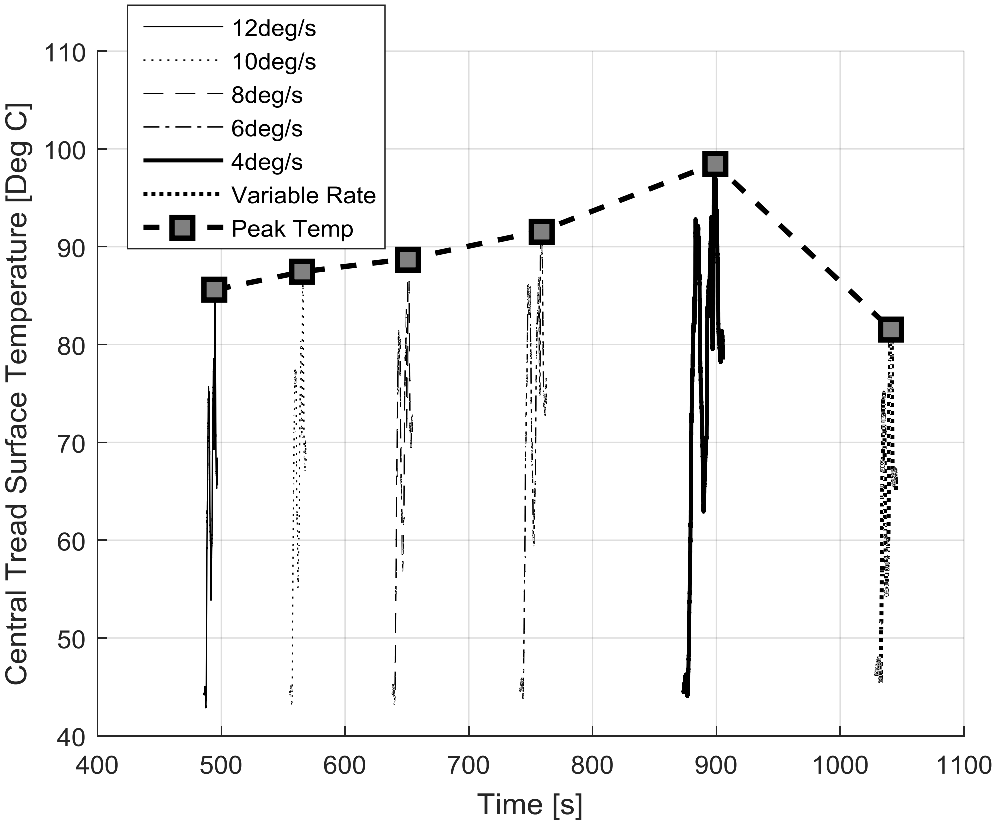
The selection of a 4 degrees threshold is supported by the work presented in [30] where the author has shown that the tyre's relaxation length reduces with slip angle and that at 4 degrees the relaxation length reduces to between 20% and 30% of its length compared to 0 degrees, whereas at 2 degrees of slip angle the relaxation length is still between 40% and 60% compared to 0 degrees. This suggests that using a faster slip angle rate at slip angles greater than 4 degrees will generate data with not only low thermal hysteresis but also the mechanical hysteresis will be low due to the significantly reduced relaxation lengths in this region. Additionally, the work presented in [30] shows that at 4 degrees the relaxation length is significantly less sensitive to vertical load than at 2 degrees. Consequently, setting the threshold at 4 degrees will be valid across a wider range of load cases. This reference also reinforces the proposal to use high slip rates at higher slip angles where the relaxation length (and hence mechanical hysteresis) is reduced.

In summary the following rates and thresholds are used:

Low speed slip angle rate:	4 deg/s
High speed slip angle rate:	12 deg/s
High/low rate threshold:	4 deg

To validate the complete variable rate sweep shape, tests were conducted comparing it to five constant slip angle rate sweeps at 4, 6, 8, 10 and 12 deg/s; these results are shown in Figure 9. The lateral force against slip angle plot between -1 and +1 degrees shows that close to 0 degrees slip angle the variable rate sweep performed as well as the best (4 deg/s) constant rate sweep, generating minimal mechanical hysteresis. At higher slip angles the results show that faster slip angle sweeps generate slightly higher lateral forces, again this is matched by the variable rate sweep. This is expected to be due to the tyre being closer to its optimal temperature during this sweep as a result of the tyre spending less time at high slip angles hence not overheating. The temperature plot shows that the variable rate sweep is the coolest throughout, having the lowest temperature variation across the sweep resulting in minimal thermal hysteresis.

In summary, the variable rate sweep generated the least mechanical hysteresis at low slip conditions resulting in the best low slip angle data; whilst also generating the lowest peak temperature and hence the least thermal hysteresis at high slip conditions resulting in better quality data throughout. Furthermore, the reduced peak temperature leads to reduced cooling times and hence a lower overall test duration.



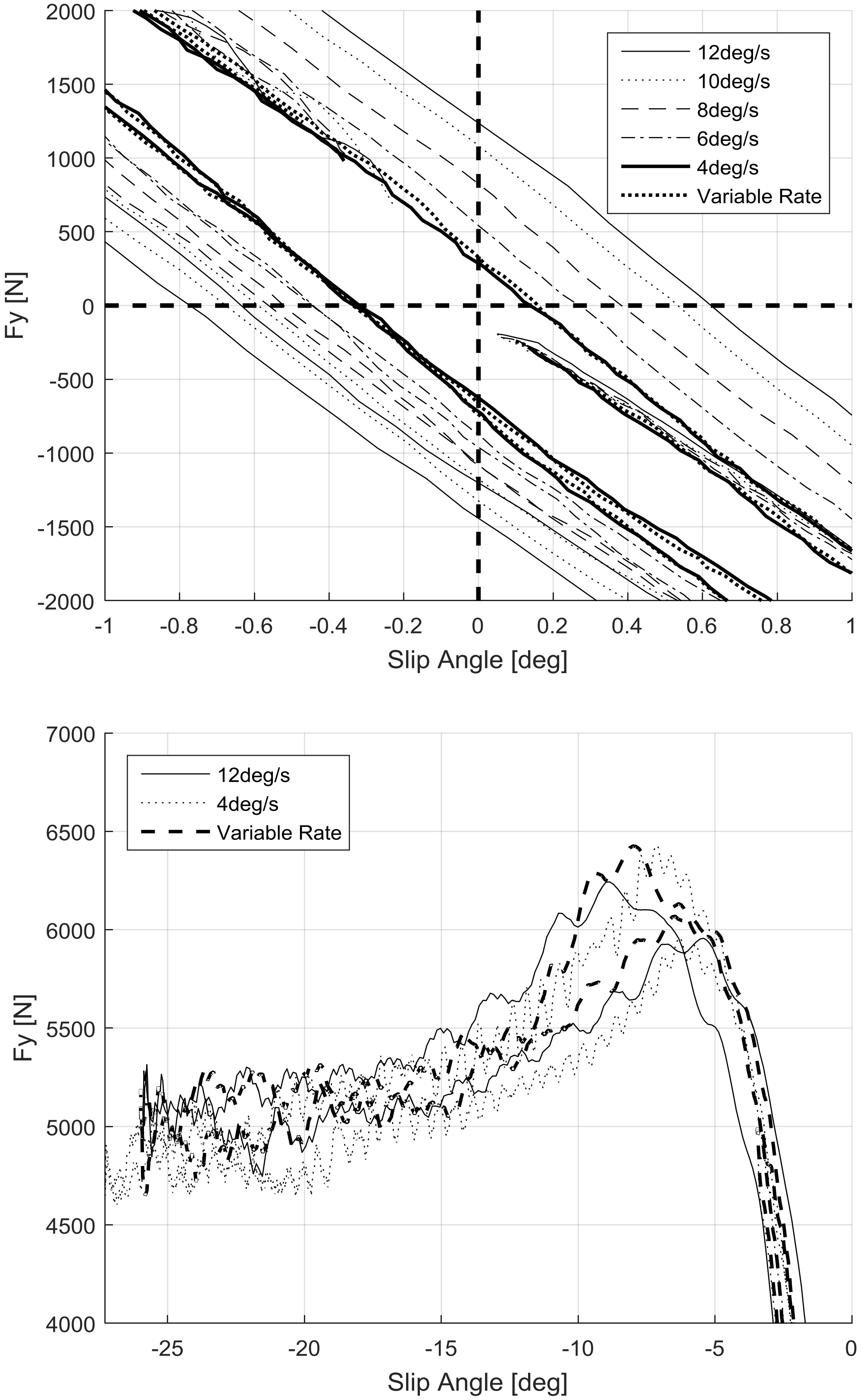


Figure 9a, 9b and 9c. A comparison of the variable slip angle rate sweep used in the GS2MF FreeRolling compared to constant rate sweeps. The influence on temperature is shown in Figure 9a - top; the influence on lateral force close to zero slip angle is shown in Figure 9b - middle and at high slip angles is shown in Figure 9c - bottom.

5.3 Sweep Shape - Fz Sweep

The majority of GS2MF FreeRolling testing is conducted at slip angles between +/- 10 degrees (shown in Figure 3) as conducting all sweeps to high slip angles would result in excessive heat and wear on the tyre. However, in order to model high slip vehicle dynamics manoeuvres the resulting MF-Tyre 6.1 tyre model is required to generate plausible results over a much higher slip angle range. The Fz sweeps introduce a favourable compromise in gathering minimal data at very high slip angles allowing the tyre model to interpolate rather than extrapolate out to 25 degrees slip angle.

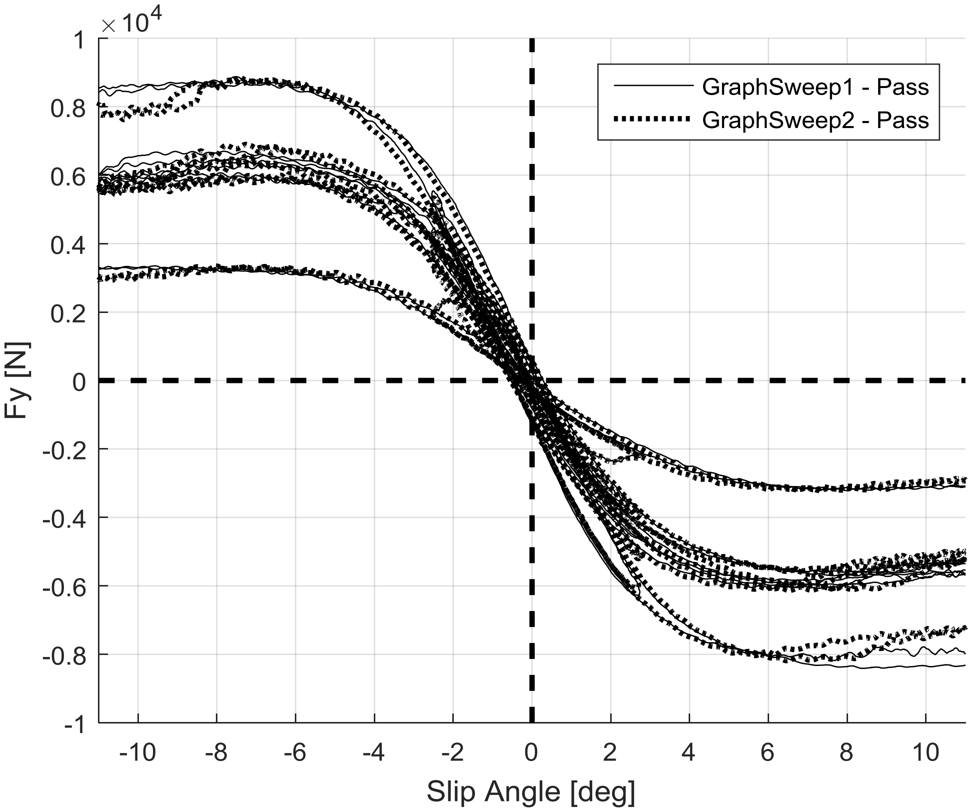
This Fz sweep approach, steers the tyre to the 18 or 25 degrees slip angle condition while generating minimal heat due to the low load of 1000 N. Whilst holding the slip angle, the load is then ramped up and down. This generates high energy data only where it is needed, rather than generating heat repetitively going to and from each high slip condition.

At the very end of the procedure two Fz sweeps are conducted at high slip angles of 25 degrees whilst also applying +6 and -6 degrees of camber. These tests generate data to maximise the operating range of the tyre model for both slip angle and camber angle. They are located at the very end of the test procedure due to the large amount of wear they place on the tyre which is then discarded.

5.4 Graph Sweeps

Graph sweeps are included in the GS2MF Free Rolling test procedure in order to judge the effect of tyre wear during the test. This involves five sweeps being conducted near the start of the test procedure which are then repeated towards the end. By overlaying the results from the two sets of identical sweeps it is possible to observe how the tyre has changed during the test. This is a useful way of ensuring the testing is consistent and that the results throughout the test are comparable. Two examples of this are shown in Figure 10.

Figure 10a shows an example of a typical test where the tyre performs similarly at the start and end of the test suggesting that the tyre has not changed significantly throughout the procedure. Figure 10b shows an example where the tyre was tested under far too high loads. In this case the tyre was highly worn after the test and the results show a significant change in the tyres' performance as a result of excessive wear. With the absence of a tyre wear model the data would not be usable to build accurate MF-Tyre 6.1 tyre models. While the data from such a test remains unusable, the inclusion of graph sweeps in the test procedure means this is known as soon as the data is obtained, therefore enabling the user to make an informed decision regarding retesting the tyre or abandoning the MF fitting.


×10^4
1
0.8
0.6
0.4
0.2
0
-0.2
-0.4
-0.6
-0.8
-1
Fy [N]
-10
-8
-6
-4
-2
0
2
4
6
8
10
Slip Angle [deg]
GraphSweep1 - Pass
GraphSweep2 - Pass

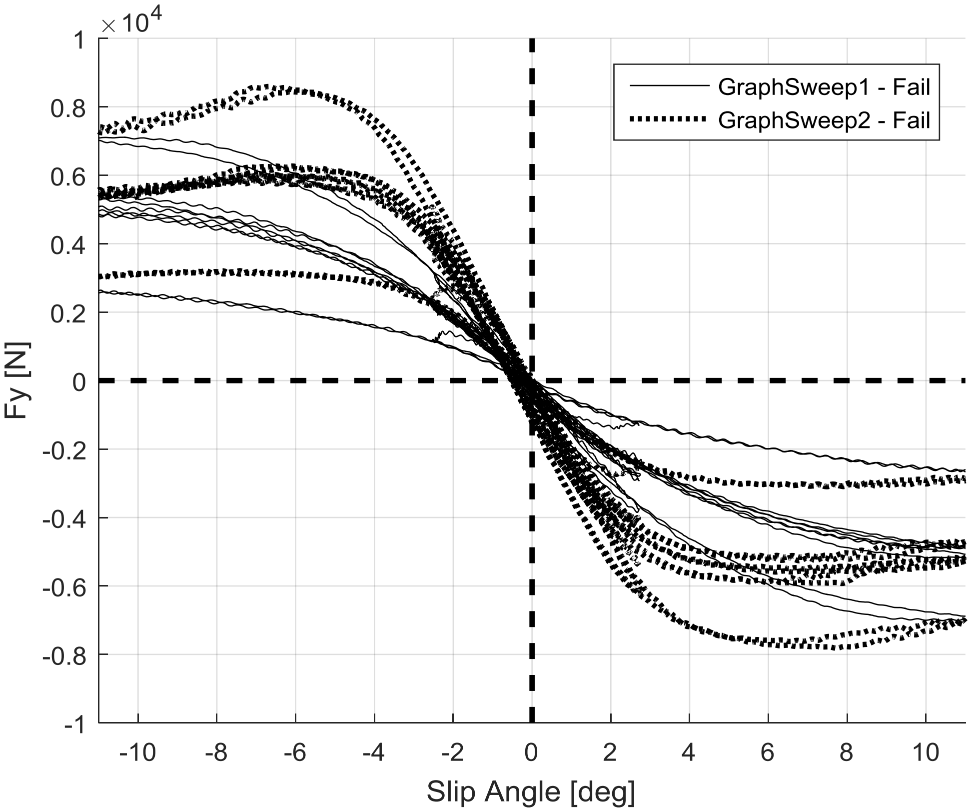
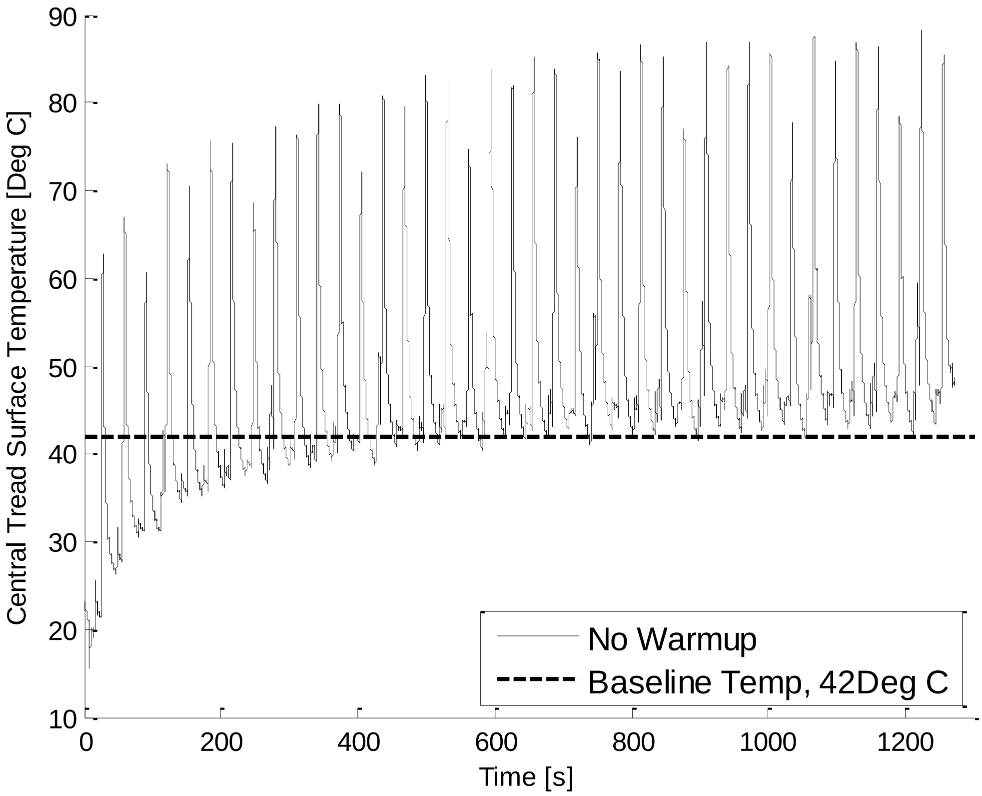

×10^4
1
0.8
0.6
0.4
0.2
0
-0.2
-0.4
-0.6
-0.8
-1
Fy [N]
-10
-8
-6
-4
-2
0
2
4
6
8
10
Slip Angle [deg]
GraphSweep1 - Fail
GraphSweep2 - Fail

Figure 10a and 10b. Example graph sweeps of test data that passes (Figure 10a - top) and fails, (Figure 10b - bottom) within a data consistency check. The failed data is due to excessive wear on the tyre.

5.5 Warmup

The warmup procedure used at the start of the GS2MF FreeRolling procedure is the first two thirds of the warmup procedure used in MICH2MF.

Testing was conducted using only the five graph sweeps continuously repeated starting from a cold tyre at 16 °C. These multiple sets of graph sweeps can be compared to each other as well as with the graph sweeps from the main GS2MF procedure. Figure 11 shows that as a result of testing, the tyre heated up until reaching a steady saturated baseline temperature (the temperature at the start of each test sweep) of around 42 °C. This indicates that under these specific test conditions the natural baseline temperature is 42Deg C, therefore a warmup procedure that heats the tyre to precisely 42Deg C is be ideal. The test was then repeated on a new tyre after using two thirds of the MICH2MF warmup procedure to warm the tyre prior to running the same series of five repeating sweeps. After the warmup section the tyre reached 38 °C and then went on to reach a baseline of 42 °C as it did without the warmup. This means that the GS2MF warmup procedure, using only two thirds of the MICH2MF warmup procedure, heated the tyre to within 4 °C of the natural baseline temperature.



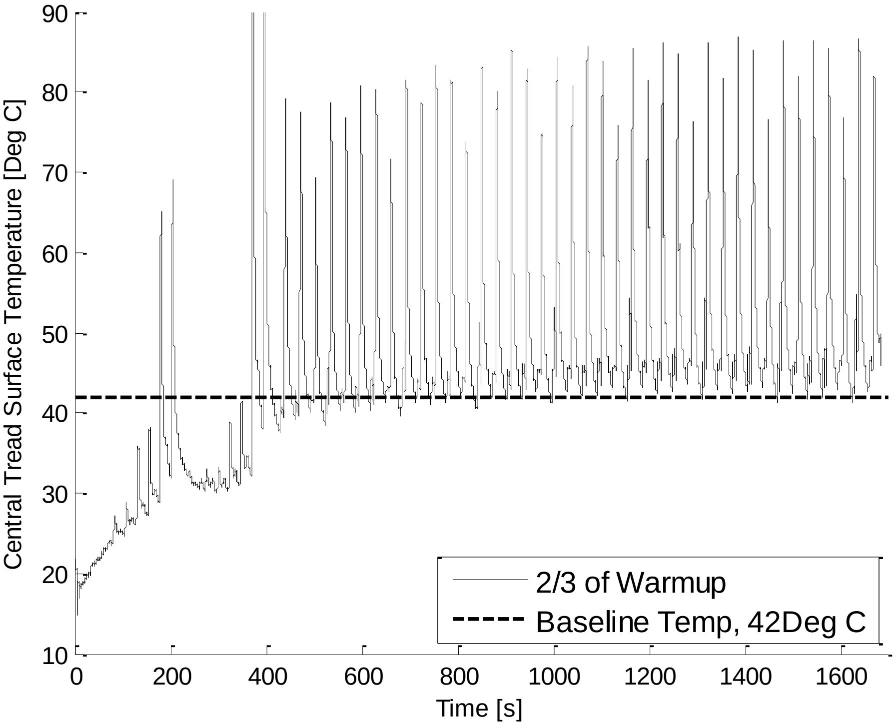
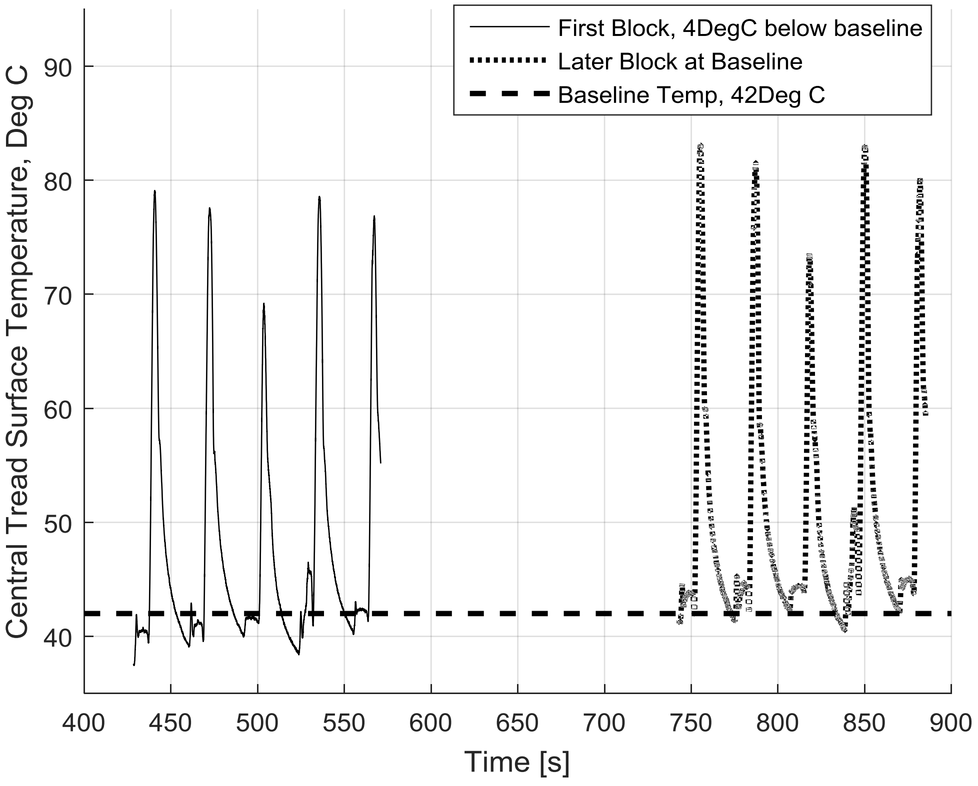
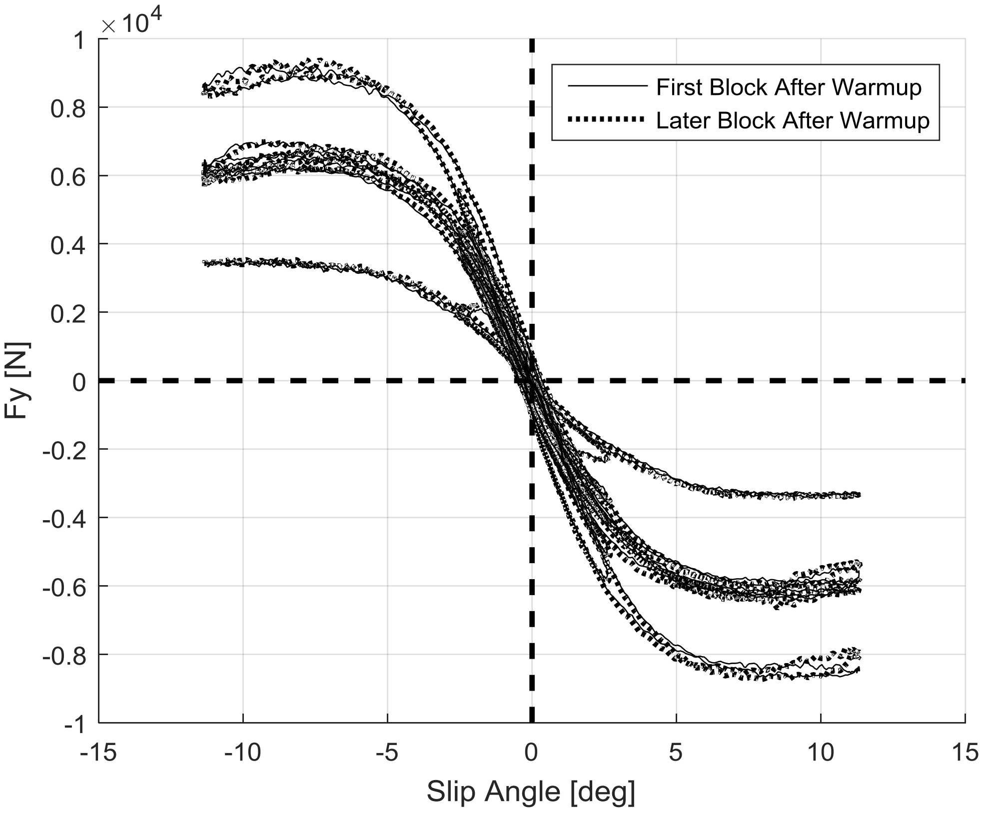


Figure 11a and 11b. Comparison of tyre temperature with the warmup procedure (Figure 11b - bottom) and without the warmup procedure (Figure 11a - top).

Further analysis was conducted to investigate if this 4 °C variation in baseline temperature significantly affected the tyre’s performance. The results in Figure 12 show a comparison of the first block of five sweeps after the warmup procedure (where the temperature was 38 °C) overlaid with a later block of the same five sweeps where the baseline tyre temperature of 42 °C was reached. The lateral force versus slip angle plot shows very little difference between the tyre’s performance. It was therefore concluded that the 4 °C temperature variation has negligible effect on tyre performance and thus two thirds of the MICH2MF warmup procedure was sufficient to adequately warm the tyre. In the interest of reducing overall rig time and tyre wear wherever possible, this shortened warmup procedure is used in GS2MF FreeRolling.



First Block, 4DegC below baseline
Later Block at Baseline
Baseline Temp, 42Deg C
Central Tread Surface Temperature, Deg C
90
80
70
60
50
40
400
450
500
550
600
650
700
750
800
850
900
Time [s]



$\times 10^4$
First Block After Warmup
Later Block After Warmup
Fy [N]
1
0.8
0.6
0.4
0.2
0
-0.2
-0.4
-0.6
-0.8
-1
-15
-10
-5
0
5
10
15
Slip Angle [deg]

Figure 12a and 12b. Overlay of two data blocks after the warmup procedure. Figure 12a – top shows the tyre's temperature; Figure 12b - bottom shows the lateral force.

5.6 Step Steer

Step steer tests are included in the GS2MF FreeRolling test procedure in order to measure the tyres' relaxation length under various conditions. The tests involve:

1. Rolling the tyre forward to relax the contact patch.
2. Stopping the tyre with the vertical load still applied.
3. Applying a 2 degrees static slip angle to the tyre.
4. Accelerating the tyre while holding the slip angle.

The lateral force build up compared to the forward distance travelled by the rotating tyre is analysed and the relaxation length can be calculated as the distance travelled until the tyre's lateral force reaches 63% of its saturated peak force. This test is repeated at five loads then each load is repeated at three inflation pressures.

Ideally the tyre will be rolling throughout the test in order to avoid any relaxation length sensitivity to forward velocity. However, if the tyre is rolling, the slip angle has to be applied instantaneously, which is impossible in a practical sense. Therefore, stopping the tyre and applying the steering statically is a practical alternative.

5.7 Cornering stiffness and vertical stiffness

Due to the cornering stiffness being of particular importance for vehicle dynamics applications special tests are integrated into GS2MF FreeRolling procedure to gather high quality cornering stiffness data. For efficiency these tests are integrated within the rolling radius tests that gather vertical stiffness data.

The cornering stiffness tests involve holding the tyre at a constant 1 degrees slip angle while the load is stepped five times. This is repeated at +1, 0 and -1 degrees slip angle and at three pre-determined inflation pressures. Holding the tyre at a constant low slip angle ensures the tyre is in a steady state condition and allows clusters of data to be collected at each of the three angles. This data aids the Magic Formula fitting algorithms to accurately capture the cornering stiffness and its sensitivities. The 0 degrees slip angle cluster, although not essential, is useful and can be used to establish any conicity or plysteer effects.

The vertical stiffness sections involve holding the tyre at a constant zero slip condition while the load is stepped four times. This is then repeated at three forward velocities and three inflation pressures. The vertical stiffness at each steady state condition can then be calculated using the distance from the test surface to the wheel centre and the vertical load channels.

5.8 General force and moment

The general force and moment section of the GS2MF FreeRolling procedure shown in Figures 3 and 4 is used along with graph sweep 1, the cornering stiffness section and the severe section to parameterise the pure lateral force and self-aligning torque parts of the

MF-Tyre 6.1 tyre model. It involves a series of variable rate free rolling sweeps at various loads and cambers, with slip angle sweeping to various maximum angles; these are then repeated at the three predetermined inflation pressures. In order to minimise testing time additional tests are conducted at the middle pressure only, such as:

- Camber angle testing at zero slip angle to gather pure camber thrust data.
- A slip angle sweep repeated with and without camber to isolate the camber effect.
- One sweep is conducted with loads adverse to its slip angle direction; where most sweeps are conducted with negative slip angles at high load (simulating a car's right side tyre steering to the left while centrifugal force shifts the car's weight to the right) and positive slip angles under lower loads. One sweep is conducted in the opposite load case in order to maximise the stability of the tyre model. This helps to ensure the model is plausible under unusual conditions such as a highly cambered road, where this load case may be possible.

The general force and moment section is the primary source of data for the Magic Formula fitting process. This is where the MF-Tyre 6.1 models are fitted to overlay the data using an optimisation algorithm.

5.9 Parameterisation

The GS2MF tyre testing procedure provides a comprehensive dataset across a suitably wide range of load cases which can then be used for the parametrisation of MF-Tyre 6.1 tyre models. Although the GS2MF procedure has been designed specifically for the MF-Tyre 6.1 version of the Magic formula tyre model, in principal it could be used to parameterise other empirical handling models such as the Harty tire model [11] or the Fiala tire model [12].

Using GS2MF data a variety of MF-Tyre 6.1 parameterisation processes can be run successfully, including the genetic algorithm used within OptimumT [31] along with other alternative approaches. The selection of a suitable fitting process is not constrained to approaches where steady state parts of MF-Tyre 6.1 are optimised separately to the relaxation lengths. If preferred, both sections can be optimised together; however, within GS2MF there exists a specific set of tests to gather relaxation length data (See Step Steer section 5.6). Therefore, regardless of the selected fitting process this section of data should be more heavily weighted when fitting the transient coefficients of MF-Tyre 6.1.

6. Conclusions

1. This paper shows that the GS2MF FreeRolling test procedure can generate higher quality data with a reduced number of tests compared to the existing square matrix approach. This has been demonstrated by the variable rate sweep generating minimal mechanical hysteresis at low slip conditions, in line with a low steering rate sweep. Application of this process also results in the generation of reduced thermal hysteresis at high slip conditions in line with a high steering rate sweep. Furthermore, this was achieved with reduced peak temperatures during the slip angle sweeps. This in turn results in shorter cool down times being required between the sweeps to allow the tyre to cool to a consistent baseline temperature, therefore leading to reduced overall test duration.

2. Asymmetry was introduced to the GS2MF FreeRolling procedure where the lateral weight transfer of a vehicle is taken into account to link slip angle with vertical load, the result being that the tyre is only tested at load conditions achievable by a vehicle. Compared to square matrix testing this effectively removes slip angle sweeps that result in irrelevant data, further reducing test duration and rig time.
3. Ancillary tests are included in the GS2MF FreeRolling procedure to capture additional cornering stiffness data, as well as vertical stiffness data and step steer data pertaining to tyre relaxation length. The integration of these tests into the new GS2MF FreeRolling procedure means that no additional testing is required to build a free rolling Magic Formula tyre model. This means that no changes in test rig configuration are required and there are no tyre changes, again minimising rig time.
4. Graph sweep tests are also included in the GS2MF FreeRolling procedure allowing the effect of tyre wear during the test to be observed by the engineers. This allows the data to be judged with respect to tyre wear hence improving confidence in the data quality.
5. Overall the GS2MF FreeRolling test procedure requires only one tyre specimen and around one hour of test rig time to gather all of the necessary data to parameterise the FreeRolling parts of an MF-Tyre 6.1 tyre model. This is a significant improvement over the 2.8 hours and six tyre specimens required when using the square matrix approach. GS2MF also improves significantly on the TIME and MICH2MF procedures which each take around three hours and use three tyres as they are not optimised to capture the influence of inflation pressure.
6. The new GS2MF procedure provides a novel contribution in the field of tyre testing and the use of tyre models in virtual vehicle design. Improving efficiency and minimising the rig time of the test processes will lead to driving down the overall cost of producing Magic Formula tyre models used in vehicle dynamics simulations. Furthermore, the improved data quality of GS2MF will ultimately contribute to greater confidence in computer vehicle simulation, as well as the pursuit for increased use of virtual models in the vehicle development process.

Acknowledgements

The authors would like to thank the following:
Jaguar Land Rover Limited, Whitley UK for funding the research and supporting the technical development, Henning Olsson, Calspan Corporation, Buffalo NY USA for general technical assistance and development, Mateo Gladstone, Jaguar Land Rover Limited, Gaydon UK for the idea of using a variable rate ‘shark tooth’ sweep shape and Alexandra Louise Stapleton-Smith, Tyre CAE and Modelling Consultants for background research and support.

References

1. Mashadi, B. and Crolla D.A. Influence of ride motions on the handling behaviour of a passenger vehicle. Proceedings of the Institution of Mechanical Engineers, Part D: Journal of Automobile Engineering, 219, 2005.
2. Cadiou JC, El Hadire A and Chikhi F. Non-linear tyre forces estimation based on vehicle dynamics observation in a finite time. Proceedings of the Institution of

Mechanical Engineers, Part D: Journal of Automobile Engineering, 218, pp1379–1392, 2004.

3. Miller, J.I. and Cebon, D. Tyre curve estimation in slip-controlled braking. Proceedings of the Institution of Mechanical Engineers, Part D: Journal of Automobile Engineering, 2015.
4. Austin, L., and D. Morrey. Recent Advances in Anti-Lock Braking Systems and Traction Control Systems. Proceedings of the Institution of Mechanical Engineers, Part D: Journal of Automobile Engineering, 214, pp. 625–38, 2000.
5. Hewson, P. Method for estimating tyre cornering stiffness from basic tyre information. Proceedings of the Institution of Mechanical Engineers Part D Journal of Automobile Engineering, 219 (12). pp. 1407-1412, 2005.
6. Mavros, G., A study on the influences of tyre lags and suspension damping on the instantaneous response of a vehicle. Proceedings of the Institution of Mechanical Engineers, Part D: Journal of Automobile Engineering, 222 (D4), pp. 485 – 498, 2008.
7. Guo, H., Bastien, C., Blundell, M. and Wood, G. Development of a detailed aircraft tyre finite element model for safety assessment. Journal of Materials and Design, v. 53, pp. 902-909, 2014.
8. Gruber, P., Sharp, R. S. and Crocombe, A. D., Friction and camber influences on the static stiffness properties of a racing tyre, Proceedings of the Institution of Mechanical Engineers, Part D: Journal of Automobile Engineering, 222, pp. 1965-1976, 2008
9. Gipser, M. FTire, a New Fast Tire Model for Ride Comfort Simulations. Proceedings of the 14th European ADAMS Users' Conference, Berlin, Germany, Nov. 1999.
10. Gallrein, A., Baecker, M., Burger, M., Gizatullin, A.: An Advanced Flexible Realtime Tire Model and its Integration Into Fraunhofer's Driving Simulator, SAE Technical Paper 2014-01-0861, 2014.
11. Blundell,M. V. and Harty, D. Intermediate tyre model for vehicle handling simulation. Proc. IMechE, Part K: Journal of Multi-Body Dynamics, 221(K1),41-62, DOI: 10.1243/14644193JMBD51, 2006.
12. Fiala, E. Seitenkrafte am rollenden Luftreifen. VDI-Zeitschrift 96, 973, 1954.
13. Pacejka HB. *Tyre and vehicle dynamics*. 2nd ed. Oxford: Butterworth-Heinemann, 2006.
14. Bakker E, Nyborg L, Pacejka HB. Tyre modelling for use in vehicle dynamics studies. Society of Automotive Engineers, 400 Commonwealth Drive, Warrendale, PA 15096, USA. 1987; SAE paper 870421.
15. Bakker E, Pacejka HB, Lidner L. A new tyre model with application in vehicle dynamics studies. In: *4th auto technologies conference*, Monte Carlo. 1989; SAE paper 890087.
16. Pacejka HB, Sharp RS. Shear force generation by pneumatic tyres in steady state conditions: A review of modelling aspects. *Vehicle System Dynamics* 1991; 20: 121-176.
17. Pacejka HB, Bakker E. The Magic Formula Tyre Model. *Vehicle System Dynamics* 1992; 21:1: 1-18.
18. Pacejka HB. The role of tyre dynamic properties. Seminar on Smart Vehicles, Delft, Proceedings: *Vehicle System Dynamics, Special Issue*.1995.

19. Pacejka HB, Besselink IJM. Magic formula tyre model with transient properties. Proc. Berlin Tyre Colloquium, *Vehicle System Dynamics Supplement 27, Swets & Zeitlinger, Lisse*. 1997: 145-155.
20. Besselink IJM, Schmeitz AJC, Pacejka HB. An improved Magic Formula/Swift tyre model that can handle inflation pressure changes. Vehicle System Dynamics. 2010; 48: 1: 337-352.
21. Milliken WF and Milliken DL. *Race Car Vehicle Dynamics*. SAE Publications, Society of Automotive Engineers, 400 Commonwealth Drive, Warrendale, PA 15096, USA, 1998.
22. Blundell MV and Harty, D. *The multibody systems approach to vehicle dynamics*. 2nd ed. Elsevier Science, 2014.
23. Calspan. Tire force and moment testing, www.calspan.comhttp://www.calspan.com/services/tire-performance-testing/force-moment-testing/ (2016, accessed 16 February 2016).
24. Bird KD, Martin JF. The Calspan Tire Research Facility: Design, development, and initial test results. *SAE Technical Paper Series* 1973.
25. MTS Corporation, Flat-Trac Tire Testing Systems, https://www.mts.com/ucm/groups/public/documents/library/dev_002227.pdf (accessed 21st April 2016)
26. Schuring, DJ, Pelz W, Pottinger, MG. The BNPS Model - An automated implementation of the “Magic Formula” concept. In: *IPC-7 conference and exposition*, Phoenix, 1993.
27. Blundell, M. V. The Modelling and Simulation of Vehicle Handling Part 3: Tyre Modelling, *Journal of Multi-body Dynamics, Proceedings of the Institution of Mechanical Engineers Vol 214 Part K, pp. 1-32, 2000.*
28. van Oosten JJM, Savi C, Augustin M, et al. TIME, Tire measurements forces and moments a new standard for steady state cornering tyre testing. In: *Vehicle systems technology for the next century*, 1999; STA99C209.
29. Buisson J. Michelin indoor characterisation for handling applied to mathematical formulae. In: *Aachener kolloquium fahrzeug- und motorentechnik*, Aachen, 2006.
30. Rill G. First order tire dynamics. In: *II European conference on computational mechanics solids, structures and coupled problems in engineering*, 2006 June 5-8; Lisbon, Portugal.
31. Ollson, H. Efficient Acquisition of Tire Data and its Application in Vehicle Handling Simulation.30th Annual Meeting and Conference on Tire Science and Technology, Akron, September 2011.