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Tyre performance analysis of a Sport 2000 MCR

Race car

Research methods (ACHA7027)

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1. Abstract

Tyre performance constitutes a fundamental element in the analysis of vehicle dynamics, as it directly influences the ability of the vehicle to achieve optimal performance. The interaction forces generated at the tyre–road contact patch govern the vehicle’s path-following behaviour; any imbalance among these forces prevents accurate trajectory tracking and may result in conditions such as understeer or oversteer.

This work presents an empirical methodology for the mathematical modelling of tyre behaviour, aimed at capturing the main performance characteristics relevant to vehicle dynamics simulations. The proposed model employs slip angle, slip ratio, camber angle, and vertical load as input variables, while the corresponding outputs include lateral force, longitudinal braking force, and self-aligning torque.

The modelling approach is based on experimental data obtained through track testing and controlled tyre testing procedures. These data are used to identify the coefficients required for the implementation in the Pacejka tyre formula. The resulting characteristic curves enable the development of a comprehensive tyre model capable of accurately representing pure braking and pure cornering conditions, as well as their combined effects.

The final tyre model is implemented within a simulation environment, and its validity is assessed through comparison with experimental vehicle data, demonstrating an adequate correlation between simulated and real-world behaviour.

2. Introduction

The SRCC Sports 2000 Duratec Championship is a racing series intended for competitors using open-cockpit, two-seater sports racing cars equipped with a standard rear-mounted Ford 2000 cc, 16-valve Duratec engine (DHE 420) in its 145 PS configuration, as specified by the official regulations [1]

Since 2022, students and staff of the University of Wales Trinity Saint David (UWTSD) have participated annually in this championship by designing and manufacturing an in-house prototype fully compliant with the prescribed technical regulations. Over the years, several aspects of the vehicle have been progressively improved, including overall mass reduction, aerodynamic development, and engine response. However, tyre performance has not received the same level of attention and remains a limiting factor.

According to the championship regulations, the only permitted tyres are manufactured by Hoosier and must be supplied exclusively by BMTR Motorsport [SRCC]. Consequently, the scope for tyre selection and optimisation is extremely limited. Furthermore, the use of proprietary tyre softening compounds or any other additives or treatments intended to enhance tyre performance is explicitly prohibited [1].

An additional challenge arises from the limited availability of detailed tyre data provided by the manufacturer. Hoosier's technical datasheets do not include all the information required for advanced tyre modelling, a common issue encountered by many racing teams. This lack of transparency reflects the highly competitive nature of the tyre manufacturing industry, in which proprietary formulations and performance-related data are closely guarded.

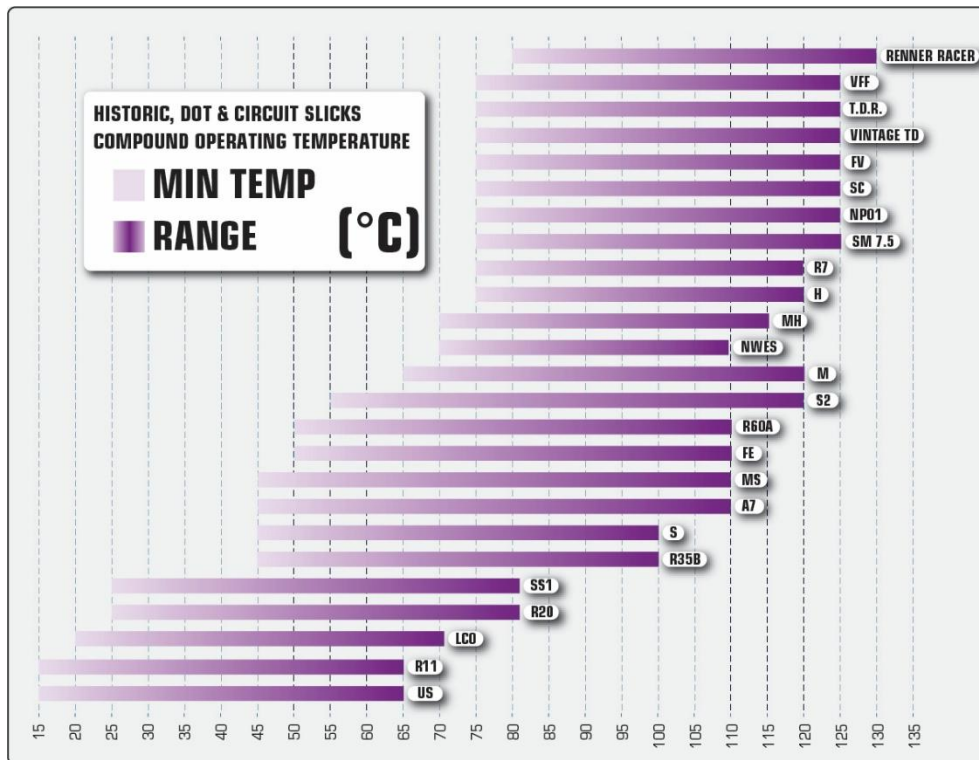


Figure 2.1: Hoosier's datasheet regarding compound operating temperature

Tyre performance represents a critical factor in determining **the** dynamic response of a vehicle. All forces acting on the vehicle during straight-line motion and, more significantly, during cornering—such as inertial loads, aerodynamic lift, and downforce—are transmitted to the ground exclusively through the tyre–road contact patches. During lateral manoeuvres, the reaction forces generated by the tyres must counteract the centrifugal forces in order to ensure stable and accurate path-following behaviour.

The importance of tyre behaviour modelling gained considerable attention during the 1980s, leading to substantial research efforts in this field. In this context, the Volvo Group commissioned a study to the Delft University of Technology, which resulted in the development of the first comprehensive mathematical formulation capable of representing the primary characteristics required for tyre modelling, known as the Pacejka “Magic Formula”. [2] The objective of this research was to enhance vehicle dynamic safety through the optimisation of stability, steering response, and braking performance by means of a coordinated tuning of chassis and tyre characteristics. Achieving this objective requires the availability of an accurate and reliable description of tyre behaviour.

The main objective of the present research is the modelling of the performance of a racing slick tyre used on a Sports 2000 MCR race car. To identify the coefficients required for the implementation of the Pacejka tyre model newly acquired track data, together with constrained tyre test data, are collected and analysed to obtain the relative coefficients. The resulting Pacejka characteristic curves are subsequently implemented within a simulation environment and validated through comparison between simulated results and experimental vehicle data.

3. Literature Review

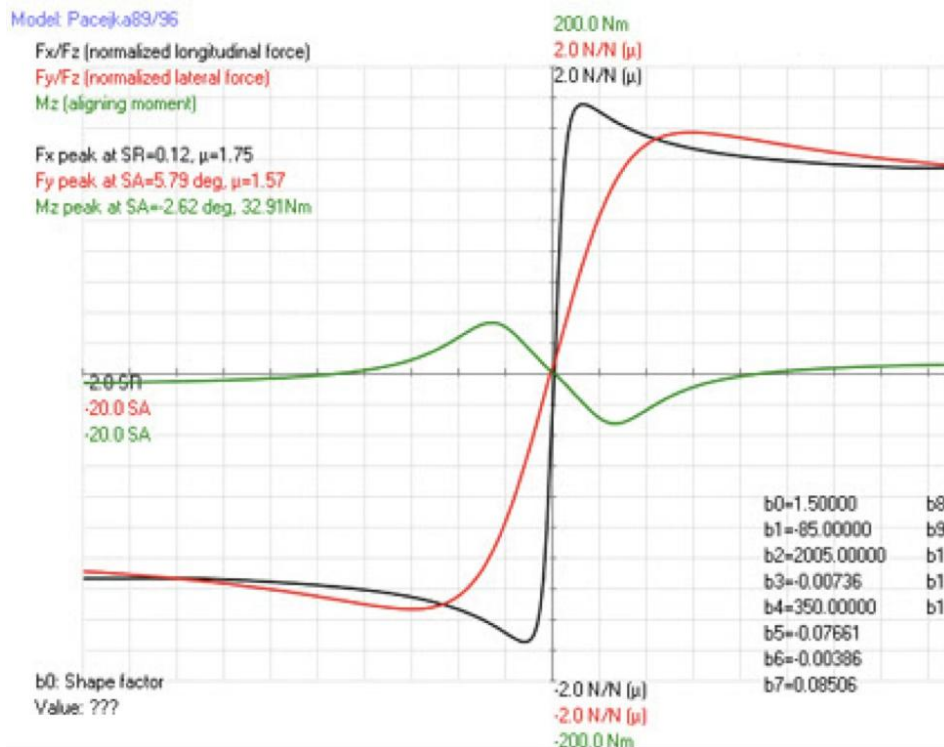


Figure 3.2.1: The Pacejka curve

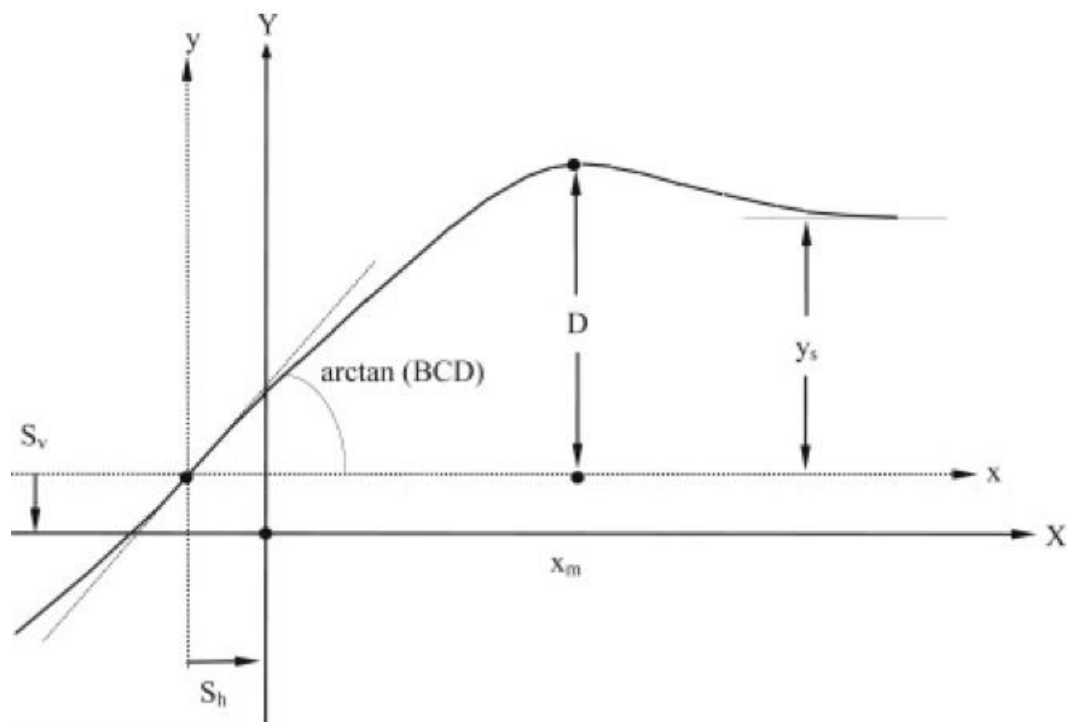


Figure 3.2: The Pacejka curve

The Pacejka tyre model was initially developed in 1987 as the outcome of a collaborative research project between the Volvo Group and the Delft University of Technology. The primary objective of this collaboration was to achieve an accurate representation of tyre behaviour, as well as its interaction with the vehicle chassis, in order to improve both vehicle performance and safety.

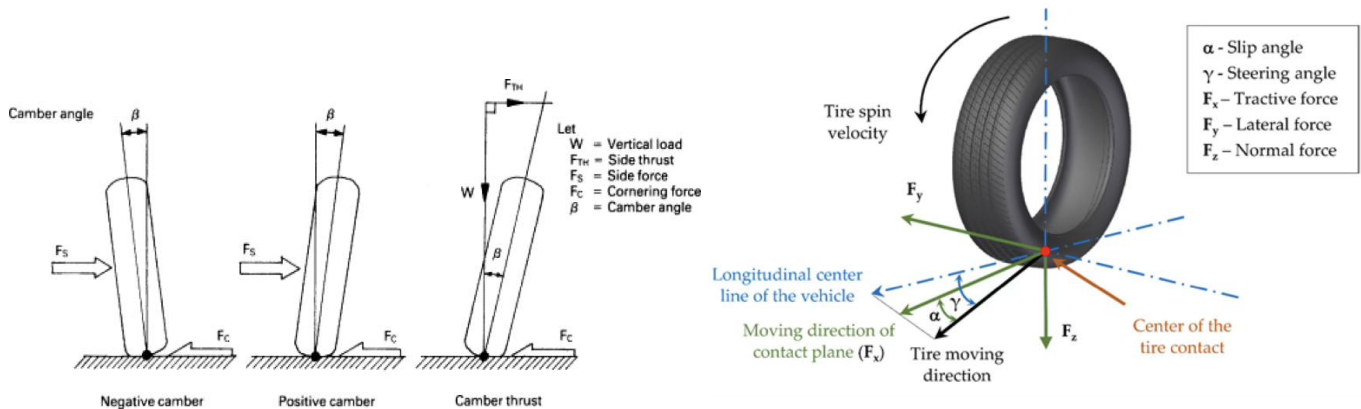


Figure 3.3: Inputs in the Pacejka Magic Formula

The Pacejka formula provides an empirical Inputs in the Pacejka Magic Formula mathematical description of tyre forces by relating key input variables—namely slip angle, slip ratio, camber angle, and vertical load—to the resulting tyre responses. The model can predict the main forces and moments acting at the tyre–road interface, specifically lateral force, longitudinal (braking) force, and self-aligning torque. These outputs form the basis for the simulation and analysis of vehicle dynamic behaviour.



Figure 3.4: Output of the Pacejka Magic Formula

Proposed tyre formulae:

$$y = D \cdot \sin[C \cdot \arctan\{Bx - E(Bx - \arctan Bx)\}] \quad (\text{Eq. 3.1})$$

$$Y(X) = y(x) + S_v \quad (\text{Eq. 3.2})$$

$$x = X + S_H \quad (\text{Eq. 3.3})$$

Where:

Y = output variable F_x , F_y or possibly M_z

X = input variable $\tan \alpha$ or k

And

B = stiffness factor

C = shape factor

D = peak value

E = curvature factor

S_H = horizontal shift

S_v = vertical shift

a_i , with $i = 1, \dots, 8$ = coefficients for tyre formula with load influence

a_m with $m=9, \dots, 13$ = coefficients for tyre formula connected with camber influence

$\bar{V}$ = direction of travel

$\bar{V}_s$ = slip speed vector

$\bar{V}_r$ = rolling speed vector

$$\bar{V} = \bar{V}_s + \bar{V}_r \quad (\text{Eq. 3.4})$$

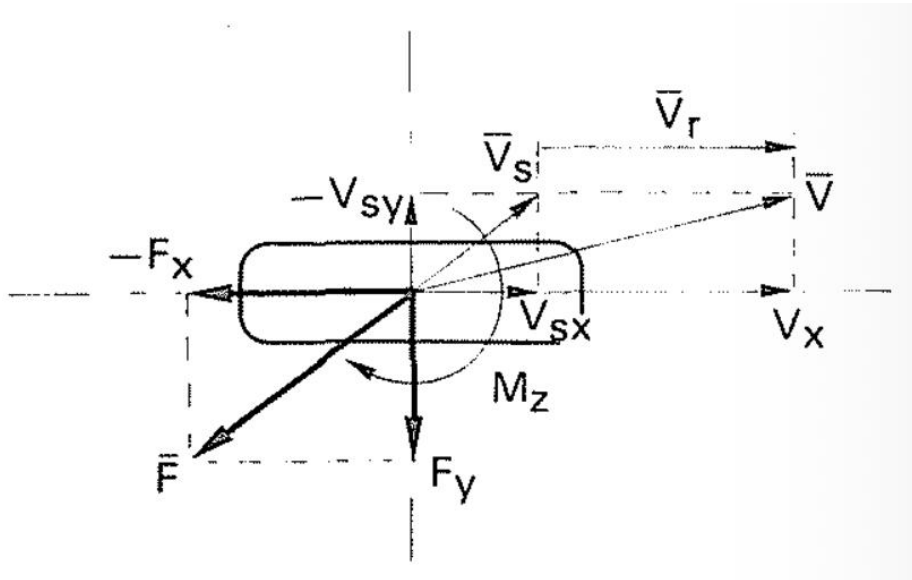


Figure 3.5: Top view of tyre during combined braking and cornering showing velocity and force vector diagrams

σ = theoretical slip

$$\sigma_x = \frac{V_{sx}}{V_r} \quad (\text{Eq. 3.5})$$

$$\sigma_y = \frac{V_{sy}}{V_r} \quad (\text{Eq. 3.6})$$

$$\sigma = \sqrt{\sigma_x^2 + \sigma_y^2} \quad (\text{Eq. 3.7})$$

α = theoretical slip

k = practical slip

$$\tan \alpha = -\frac{V_{sy}}{V_x} \quad (\text{Eq. 3.8})$$

$$k = -\frac{V_{sx}}{V_x} \quad (\text{Eq. 3.9})$$

Side Force:

$$F_y = D \cdot \sin(C \cdot \arctan(B \cdot \phi)) + \Delta S_v \quad (\text{Eq. 3.10})$$

with

$$(\text{Eq. 3.12})$$

$$\phi = (1 - E)(\alpha + \Delta S_h) + (E/B) \arctan(B(\alpha + \Delta S_h))$$

$$D = a_1 F_z^2 + a_2 F_z \quad (\text{Eq. 3.13})$$

$$C = 1.30 \quad (\text{Eq. 3.14})$$

$$B = \left(\frac{a_3 \sin(a_4 \arctan(a_5 F_z))}{CD} \right) (1 - a_{12}|y|) \quad (\text{Eq. 3.15})$$

$$E = \frac{(a_6 F_z^2 + a_7 F_z + a_8)}{(1 - a_{13}|y|)} \quad (\text{Eq. 3.16})$$

$$\Delta S_h = a_9 y \quad (\text{Eq. 3.17})$$

$$\Delta S_v = (a_{10} F_z^2 + a_{11} F_z) y \quad (\text{Eq. 3.18})$$

Self-Aligning Torque:

$$F_y = D \cdot \sin(C \cdot \arctan(B \cdot \phi)) + \Delta S_v \quad (\text{Eq. 3.19})$$

With

$$\phi = (1 - E)(\alpha + \Delta S_h) + (E/B) \arctan(B(\alpha + \Delta S_h)) \quad (\text{Eq. 3.20})$$

$$D = a_1 F_z^2 + a_2 F_z \quad (\text{Eq. 3.21})$$

$$C = 2.40 \quad (\text{Eq. 3.22})$$

$$B = \left(\frac{a_3 F_z^2 + a_4 F_z}{C D e^{a_5 F_z}} \right) (1 - a_{12} |y|) \quad (\text{Eq. 3.23})$$

$$E = \frac{(a_6 F_z^2 + a_7 F_z + a_8)}{(1 - a_{13} |y|)} \quad (\text{Eq. 3.24})$$

$$\Delta S_h = a_9 y \quad (\text{Eq. 3.25})$$

$$\Delta S_v = (a_{10} F_z^2 + a_{11} F_z) y \quad (\text{Eq. 3.26})$$

Brake force:

$$F_y = D \cdot \sin(C \cdot \arctan(B \cdot \phi)) \quad (\text{Eq. 3.27})$$

With

$$\phi = (1 - E)k + (E/B) \arctan(Bk) \quad (\text{Eq. 3.28})$$

$$D = a_1 F_z^2 + a_2 F_z \quad (\text{Eq. 3.29})$$

$$C = 1.65 \quad (\text{Eq. 3.30})$$

$$B = \left(\frac{a_3 F_z^2 + a_4 F_z}{C D e^{a_5 F_z}} \right) \quad (\text{Eq. 3.31})$$

$$E = a_6 F_z^2 + a_7 F_z + a_8 \quad (\text{Eq. 3.32})$$

4. Aims/Objectives

The objective of this research is to identify and define the coefficients that characterise the main physical properties of a tyre, including parameters such as cornering stiffness at zero slip, peak force values, and self-aligning torque characteristics. These coefficients are required to accurately predict tyre performance and force generation under a wide range of operating conditions.

Once identified, the coefficients are incorporated into the Pacejka tyre formula and implemented within vehicle simulation software used for the analysis of race car performance during competitive events. The accuracy and reliability of the resulting tyre model are subsequently assessed through comparison between simulation outcomes and experimental data obtained from real-world testing.

5. Methodology

5.1 Proposed GANTT and track testing

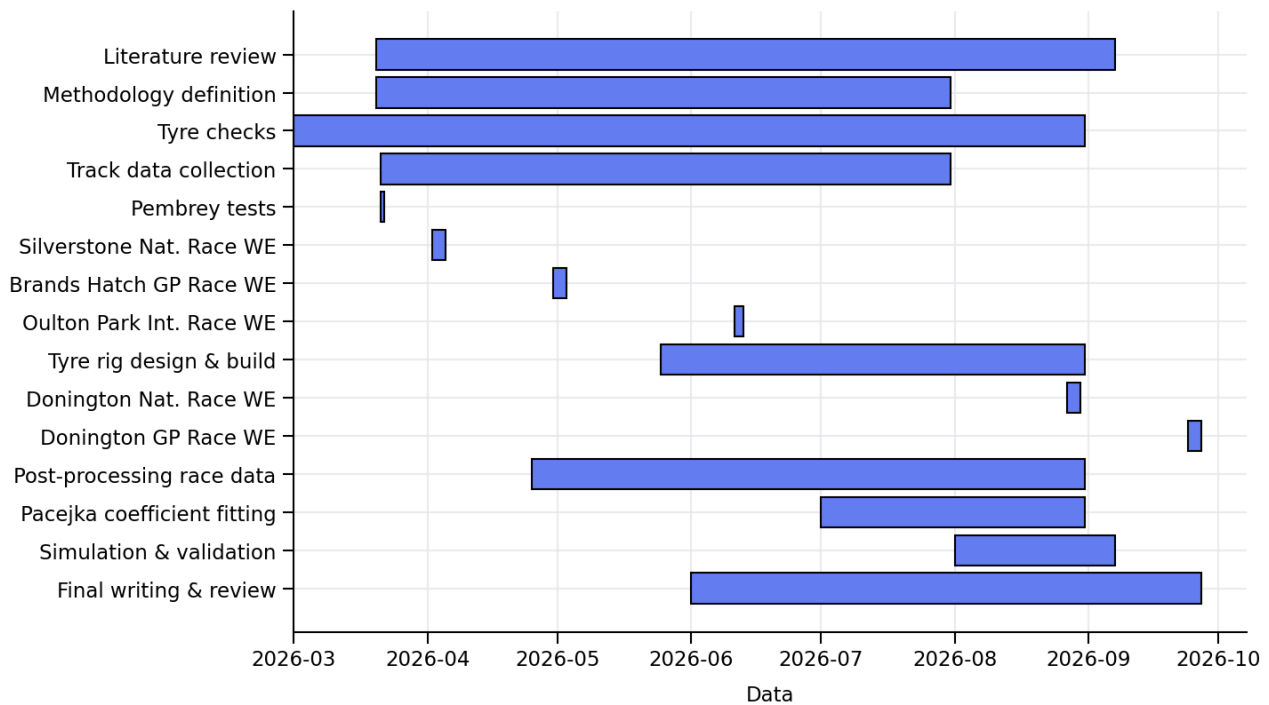


Figure 0.1: CAN Tyre Pressure Monitoring System (TPMS)
Motorsport 3 sets of wheels

The Gantt schedule is primarily based on the availability of track data to be collected during the 2026 racing season using the CAN Tyre Pressure Monitoring System (TPMS) installed on wheel sets. As this type of data was not collected in previous seasons, it is necessary to rely on data acquisition during race weekends.

In parallel, these events provide an opportunity to collect qualitative information through semi-structured driver interviews. This interview methodology allows feedback to be gathered using a predefined set of guiding questions while retaining sufficient flexibility to explore specific topics in greater depth. Such an approach is particularly suitable for investigating qualitative aspects that are difficult to quantify, including vehicle drivability, tyre degradation on a lap-by-lap basis, track surface characteristics, and the influence of extraneous variables. These variables include any factors not directly controlled within the study—such as track conditions, race interruptions (e.g. red flags), incidents, and weather—which may nevertheless affect the outcomes of the analysis.

A limitation of the experimental framework is that several controlled vehicle parameters, including suspension settings, front splitter configuration, and rear wing adjustment, must be modified for each race event to accommodate track-specific characteristics such as circuit layout, the distribution of left- and right-hand corners, track elevation profile, tarmac age and consistency, and the overall aerodynamic downforce requirement. As these factors have a direct impact on tyre performance and wear, it becomes necessary to complement the newly acquired track data with additional tyre datasets to ensure a robust and representative tyre performance analysis.



[Figure 0.2: GANTT for the research proposal]

As the Donington Park GP event is scheduled to take place during the final week of September, the track data collected during this race weekend will fall outside the scope of the present research, as the viva examination is planned to occur prior to this date. Consequently, these data will not be included in the modelling and validation activities discussed in this work.

The experimental data collected throughout the season are analysed using MoTeC software for initial inspection and visualisation, followed by post-processing in MATLAB. This

processing pipeline is employed to identify the coefficients required for the implementation of the tyre model. The identification procedure is conducted progressively: initially, the tyre force characteristics are analysed without considering the influence of vertical load; subsequently, the effect of vertical load is introduced; finally, camber angle dependence is incorporated.

For each stage of the analysis, characteristic curves describing lateral force, self-aligning torque, and longitudinal (braking) force behaviour are generated. These quantities represent the dependent variables of the study and are modelled using the selected tyre formulation, which accounts explicitly for the influence of vertical load. This structured approach enables a systematic assessment of the contribution of each operating parameter to overall tyre performance.

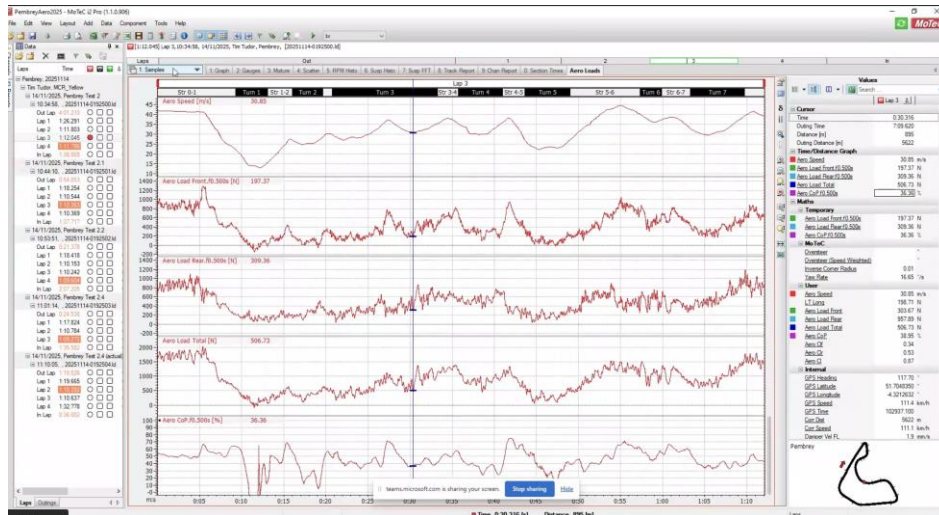


Figure 5.1.0.3: MoTec Software

Table 1
Coefficients for tyre formula (first fit)
(α [deg.], κ [%])

	LOAD (kN)	B	C	D	E	S_h	S_v	BCD
F_y	2	0.244	1.50	1936	-0.132	-0.280	-118	780.6
	4	0.239	1.19	3650	-0.678	-0.049	-156	1038
	6	0.164	1.27	5237	-1.61	-0.126	-181	1091
	8	0.112	1.36	6677	-2.16	0.125	-240	1017
M_z	2	0.247	2.56	-15.53	-3.92	-0.464	-12.5	-9.820
	4	0.234	2.68	-48.56	-0.46	-0.082	-11.7	-30.45
	6	0.164	2.46	-112.5	-2.04	-0.125	-6.00	-45.39
	8	0.127	2.41	-191.3	-3.21	0.009	-4.22	-58.55
F_x	2	0.178	1.55	2193	0.432	0.000	25.0	605.0
	4	0.171	1.69	4236	0.619	0.000	70.6	1224
	6	0.210	1.67	6090	0.686	0.000	80.1	2136
	8	0.214	1.78	7711	0.783	0.000	104	2937

Table 2
Coefficients for tyre formula (with load influence)
(F_z [kN])

	a_1	a_2	a_3	a_4	a_5	a_6	a_7	a_8
F_y	-22.1	1011	1078	1.82	0.208	0.000	-0.354	0.707
M_z	-2.72	-2.28	-1.86	-2.73	0.110	-0.070	0.643	-4.04
F_x	-21.3	1144	49.6	226	0.069	-0.006	0.056	0.486

Table 3
Coefficients for tyre formula connected with camber influence
(γ [deg.])

	a_9	a_{10}	a_{11}	a_{12}	a_{13}
F_y	0.028	0.000	14.8	0.022	0.000
M_z	0.015	-0.066	0.945	0.030	0.070

These coefficients are subsequently compared against the corresponding measured experimental data in order to assess the accuracy of the tyre model.

Since the Pacejka “Magic Formula” was originally developed under pure braking and pure cornering conditions, and later extended to represent combined slip events, a high level of model validity and repeatability is required. To achieve this, an additional phase of experimental testing is necessary.

This phase involves the design and construction of a constrained tyre testing rig using the dyno system available in the UWTSD workshop. The controlled testing environment allows tyre behaviour to be investigated under repeatable conditions, reducing the influence of external variables and supporting the accurate identification of tyre model coefficients.

5.2 Construction of Constrained Tyre Testing Rig

Constrained tyre testing rigs are commonly used to evaluate tyre behaviour and durability under a wide range of load conditions. Commercially available professional rigs are extremely expensive, with costs typically ranging from approximately £30,000 to over £200,000, depending on their accuracy and degrees of freedom. Due to these prohibitive costs and to motorsport regulations that often restrict the use of such equipment by racing teams, tyre testing rigs are generally owned exclusively by tyre manufacturers, making them relatively uncommon.

Although the design and construction of a constrained tyre testing rig for UWTSD would present significant challenges, it is technically feasible. Moreover, since the Sports 2000 Duratec regulations do not prohibit the use of tyre testing rigs, the development of such a system would represent a significant benefit, not only for the present research but also for future projects within the team.

The proposed constrained tyre testing rig would consist of five main subsystems. The load frame would provide the structural support and locate the other components. The force hub would be responsible for measuring forces and moments acting on the tyre. The steering mechanism would generate the required slip angles during testing, while the loading mechanism would apply and vary the vertical load on the tyre. Finally, the data acquisition and control system would manage sensor inputs, actuator commands, and data storage throughout the tests.

force hub is considered the most suitable option due to its high accuracy and dynamic response.

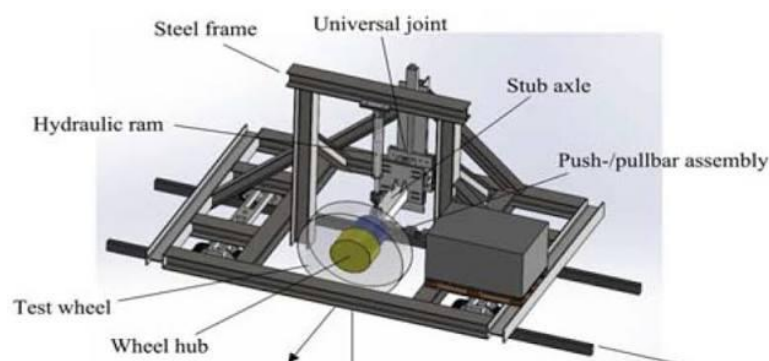


Figure 5.2.1: Proposed constrained testing tyre rig



Figure 5.2.2: *In-house produced constrained tyre testing rig*

6. Expected Results

By comparing the identified tyre coefficients with the corresponding lateral force, self-aligning torque, and longitudinal braking force characteristics, it becomes possible to describe key relationships such as lateral and longitudinal force as a function of slip ratio, lateral force as a function of braking force, and self-aligning torque as a function of braking force at defined slip angles.

To validate the obtained Pacejka curves and the corresponding coefficients, the tyre model is implemented within a vehicle simulation environment, and the simulation results are compared against real-world experimental data. By incorporating detailed information regarding the racetrack characteristics, vehicle setup, and the fitted Pacejka model, the simulator can reproduce vehicle performance under specific operating conditions.

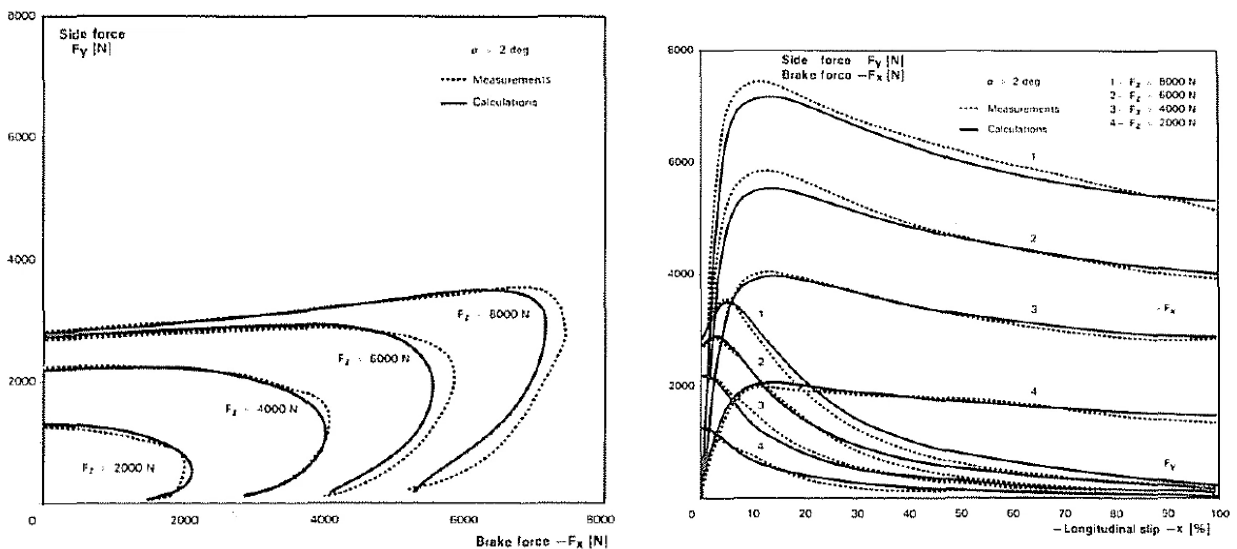


Figure 6.0.1: Expected graphs (a) Side force vs brake force at 2 degrees slip angle, (b) Side force and break force vs longitudinal slip at 2 degrees slip angle

Commercial vehicle simulation software typically employs generic tyre models based primarily on analytical or semi-empirical formulations. While suitable for general studies, such models are often less accurate when applied to a specific tyre compound, as in the present case, where tyre behaviour must be characterised using empirical data.

The comparison between simulated results and track data enables the identification of agreements and discrepancies, as well as the investigation of their causes. These discrepancies are commonly associated with external factors such as weather conditions,

track surface variations, and unforeseen race events, including accidents, red flags, and race restarts.

For this reason, the use of a constrained tyre testing rig is considered essential to support the validation of track data by providing a controlled and repeatable testing environment, thereby improving the reliability of the identified tyre model.

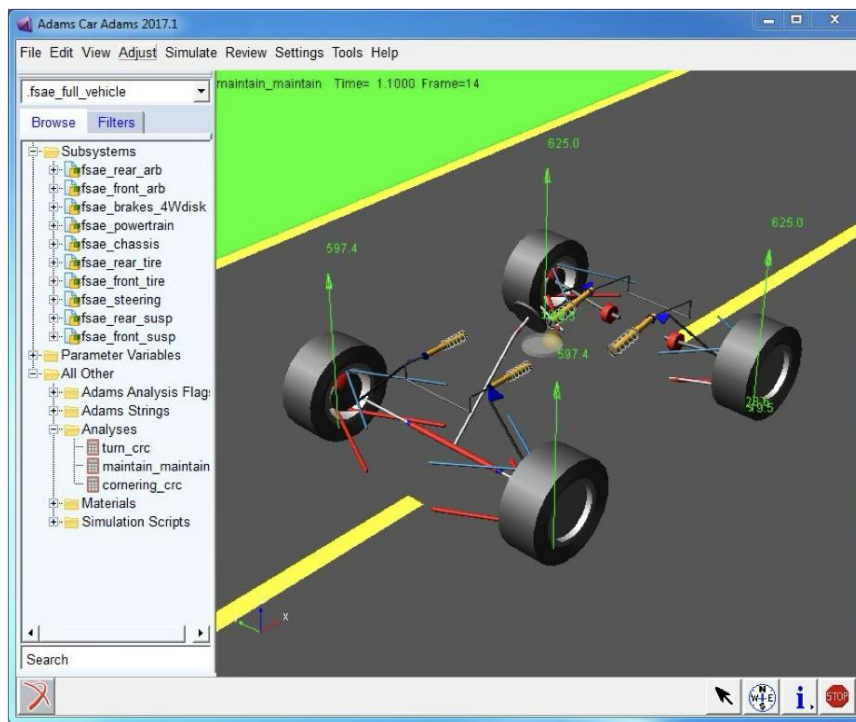


Figure 6.2: Commercially available Vehicle dynamics simulator

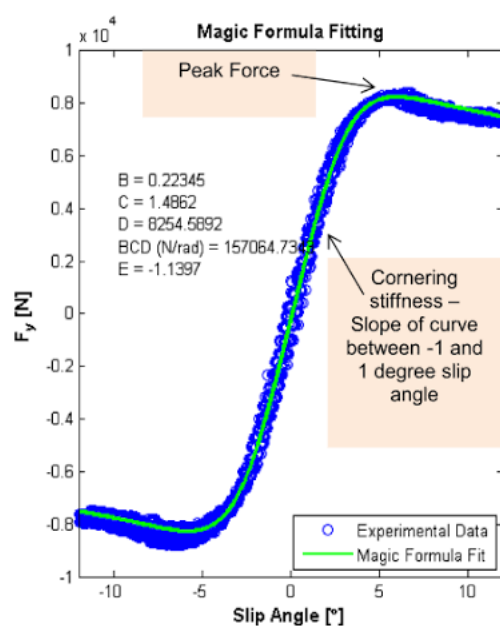


Figure 6.3: Expected comparison between experimental data and the Magic Formula Fit

6. Conclusions

Tyre performance analysis is a necessary activity for the MCR team, as the tyre manufacturer Hoosier does not provide a comprehensive datasheet containing all the data required for detailed vehicle dynamics studies. As a result, tyre behaviour must be characterised directly through experimental analysis.

Track data collected during test sessions and race events, together with data obtained from a constrained tyre testing rig, are used to identify the Pacejka characteristic curves and determine the corresponding model coefficients. These empirically derived coefficients are then implemented within a vehicle dynamics simulation software, enabling a direct comparison between the simulated tyre behaviour and real-world experimental data.

The expected outcome of this process is a reliable and representative description of tyre behaviour under racing conditions. While the developed model provides a solid basis for performance analysis, further research may focus on the development of more advanced simulation frameworks capable of accounting for additional factors such as track surface conditions, weather variability, and other environmental influences.

7. References

[1]	SRCC Sports 2000 Duratec Championship Regulations
[2]	Bakker, E. and Nyborg, L. and Pacejka, H. B., 1987, 'Tyre Modelling for Use in Vehicle Dynamic Studies', SAE Technical Paper no. 870421
[3]	Russow, M., 2015, 'Development of a Tyre and Vehicle Dynamics Model for Formula SAE', SAE Technical Paper no. 2015-01-007
[4]	Pacejka, H.B. (2005) <i>Tyre and Vehicle Dynamics</i> . Warrendale, PA: SAE International. ISBN 0-7680-1702-5. 2005.
[5]	Haney, P. (2003) <i>The Racing and High Performance Tire</i> . Warrendale, PA: SAE International. ISBN 0-7680-1241-4.
[6]	Lugner, P., Pacejka, H.B. and Plöchl, M. (2005) 'Recent advances in tyre models and testing procedures', <i>Vehicle System Dynamics</i> , 43(6–7), pp. 413–436.
[7]	Gardner, E.R. (1975) 'Tyres: general developments, materials, manufacture', <i>Progress of Rubber Technology</i> , 38, pp. 35–37.