

This is an author's preprint of the following publication as archived in the DLR electronic library at <http://elib.dlr.de>: Bünthe, Rill, Ruggaber, Tobolar: Modelling and Validation of the TMeasy Tyre Model for Extreme Parking Manoeuvres, presented on the 27th IAVSD International Symposium on Dynamics of Vehicles on Roads and Tracks, 2021.

August, 2021

# Modelling and Validation of the TMeasy Tyre Model for Extreme Parking Manoeuvres

Tilman Bünte<sup>1</sup>, Georg Rill<sup>2</sup>, Julian Ruggaber<sup>1</sup>, and Jakub Tobolár<sup>1</sup>

<sup>1</sup> German Aerospace Center (DLR),  
Institute of System Dynamics and Control, Wessling, Germany,  
`Tilman.Buente@DLR.de`

<sup>2</sup> Ostbayerische Technische Hochschule (OTH), Regensburg, Germany

**Abstract.** The TMeasy is a tyre model suitable for vehicle handling analyses and enables easy parametrisation. Recently, a convenient interface to Modelica was implemented by DLR to support the TMeasy also for vehicle modelling in multi-physical domains. This paper focuses especially on the particular problem of reliable reproduction of the tyre's bore torque which occurs during parking manoeuvres. It outlines the theory behind it, discusses the Modelica interface implementation, and presents the results of parameter identification which were achieved based on real experiments with DLR's research platform ROboMObil.

**Keywords:** tyre model, vehicle modelling, parameter identification, TMeasy, Modelica, parking manoeuvre, ROboMObil

## 1 Introduction

In vehicle dynamics modelling and simulation, tyre models play a crucial role to obtain reliable results. Over the last decades, various problem-specific tyre models have been developed and enhanced, reaching from the simplest models with few parameters to complex ones which involve the finite elements theory. A survey of the models and a benchmark-based comparison can be found e.g. in [8]. One of the models evaluated in this paper – the TMeasy – is established upon a semi-physical approach and suits well for vehicle handling evaluations.

Modelica is an object-oriented and equation based programming language which facilitates modelling of complex multi-physical systems. Focusing on automotive applications, the various domains such as multi-body vehicle dynamics, hybrid power train, brake thermodynamics, etc. can be seamlessly combined. Consequently, the need for suitable tyre models has been achieved by either reimplementing of known models in Modelica, [2], or by development of suitable interfaces for proprietary models, [5], in the past. Regarding TMeasy, some previous reimplementations in Modelica have also been realised [14, 1] which even distinguish various problem-specific levels of detail.

Since a reimplementing always lacks the link to a continuing development of the original model we show yet another approach to bridge this gap in the present paper – an implementation of a suitable Modelica interface to TMeasy. As a use

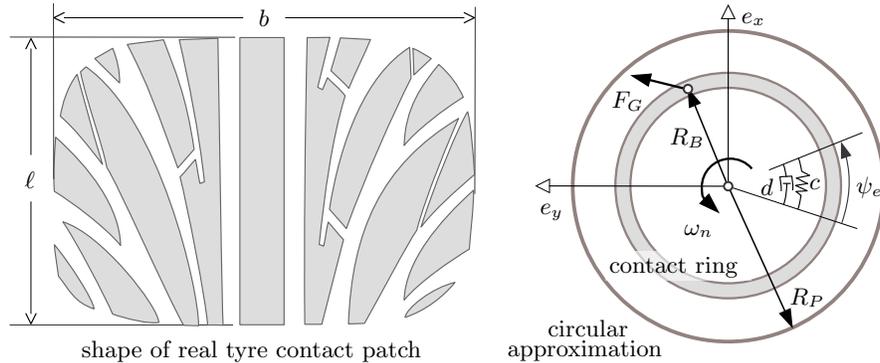
case, we investigate the bore torque properties and identify parameters of the TMeasy model for a specific Nankang passenger car tyre with particular focus on parking manoeuvres. The paper introduces the theory of the TMeasy in Sect. 2.1, followed by comments on the implementation in Modelica, Sect. 2.2. Parameter identification is discussed in Sect. 3, based on virtual testing (Sect. 3.1) and on a real driving manoeuvre (Sect. 3.2). Sect. 4 concludes the paper.

## 2 TMeasy and its Interface to Modelica

TMeasy represents a handling tyre model based on a semi-physical approach. It combines the normalised longitudinal, lateral, and turn slips into a three-dimensional slip and the embedded tyre dynamics provides a smooth transition from stand still to normal driving situations, [13]. The theory behind the bore torque modelling and the Modelica interface to the TMeasy C-code are given in the following.

### 2.1 First Order Dynamics of the Bore or Turn Torque with the TMeasy Tyre Model

A simple but effective dynamic turn torque model generates realistic parking torques in addition. The roughly rectangular contact patch of width  $b$  and length  $\ell$  is approximated by a circle of radius  $R_P = (b/2 + \ell/2)/2$ , see Fig. 1. Assuming a constant pressure distribution, the circular approximation can fur-



**Fig. 1.** Contact patch footprint of a passenger car tyre Nankang 165/35 R17 at  $F_z = 2460$  N (left) and TMeasy tyre model circular approximation with equivalent contact ring (right).

ther be simplified to a contact ring of radius  $R_B = 2/3R_P$  which is attached to a

fictitious non-spinning rim body by a torsional spring damper combination. The fictitious rim body rotates only about the normal of the local road plane. Then

$$\tau_B = c \psi_e + d \dot{\psi}_e \quad (1)$$

delivers the dynamic bore torque, where  $c$  and  $d$  characterise the torsional stiffness and damping properties of the tyre, respectively. The first order differential equation

$$\left( (r_D |\Omega| + v_N) d + R_B^2 f_G \right) \dot{\psi}_e = - (r_D |\Omega| + v_N) c \psi_e - R_B^2 f_G \omega_n \quad (2)$$

finally defines the torsional angle  $\psi_e$  as described in [13] where  $\omega_n$  denotes the angular velocity of the rim normal to the effective local road plane,  $r_D$  is the dynamic rolling radius, and  $\Omega$  is the wheel spin angular velocity. The small fictitious velocity  $v_N > 0$  avoids singularities at stand still ( $\Omega = 0$ ) and the global derivative  $f_G$  of the generalised tyre force  $F_G$  depends also on the longitudinal and lateral slips. A wheel load depending adjustment factor  $\lambda_{RB} = \lambda_{RB}(F_z)$  multiplied to the bore radius ( $R_B \rightarrow \lambda_{RB} R_B$ ) makes it possible to adjust the bore or turn torque to measurements.

The standard version 5.3 of TMeasy applies a similar approach to the longitudinal and lateral directions, thus generating first order tyre dynamics as default. The extended version 6.0 expands the standard tyre model by the first two rigid body eigenmodes of the belt which represent the in-plane longitudinal and rotational movements of the belt relative to the rim. Consequently, the dynamics of the longitudinal force is of higher order, [12]. The parameters of the TMeasy tyre model have a physical meaning and may even be estimated by a skilled engineer if no measurements are available. The TMeasy parameters can nevertheless be adjusted to tyre or vehicle dynamics measurements. As a part of the work shown here, TMeasy was implemented in the framework of the multi-physics Modelica modelling standard and DLR vehicle dynamics models, regarding specific requirements following from the modelling approach.

## 2.2 TMeasy Implementation in Modelica

Recognising earlier Modelica realisations [14, 1] of the TMeasy tyre model, a novel implementation based on TMeasy version 6.0 was made here. In the multi-physics modelling language Modelica [9] procedural code can easily be included into models either in the form of native Modelica algorithm sections or by calling external functions written in C or FORTRAN 77. Since all parts of TMeasy are provided as C functions, integration into Modelica is straightforward. However, a challenge arises due to differing model structures used in the two realms. In Modelica, the tyre/road contact is preferably handled using the VehicleInterfaces library [4]. Here, the road is represented by an *outer class* providing a global replaceable road model. Then, any tyre model in Modelica calls outer road interface functions to calculate the contact point including the road normal, friction coefficient, heading direction, etc. On the other hand, in TMeasy the tyre/road contact is calculated based on a function which determines the

so-called *effective local road plane* [12]. Normally, the latter function is called as a part of the tyre forces (and torques) calculation. Therefore, the TMeasy road contact calculation needed to be disassembled from the calculation of forces. To be more precise, the single TMeasy C function `tmy_core_dyn` providing both the contact and the forces calculation was split into two parts. The first part calculating the effective local road plane was implemented as a Modelica algorithm which allows for calling the outer road functions as outlined above. The second part remains C code but receives the contact variables as inputs and is called via the Modelica external function interface. The rest of the TMeasy C routines remain untouched.

### 3 Tyre Parameter Identification

There exists a range of physical test procedures to identify tyre characteristics, such as drum tests to determine the steady-state tyre behaviour. Based on these characteristics, a parameter identification of a particular tyre model yields the necessary values. For commercial tyre models, model-specific identification procedures are often available.

#### 3.1 Tyre Parameter Identification Framework

In most practical applications, either measured force/torque slip characteristics or the parameter sets for an alternative tyre model are available. In the following, an optimisation based framework is presented which allows conversion of the available data to the TMeasy 6.0 parametrisation. As an example, tyre characteristic curves generated by the widely used Magic Formula 5.2 (MF) from Pacejka [10] are used as a reference. The workflow diagram of the framework is shown in Fig. 2. The starting point of the identification process is the reference data for the tyre longitudinal and lateral force  $F_x^*(\kappa)$  and  $F_y^*(\alpha)$  characteristics, respectively, as well as the tyre self-aligning torque  $\tau_z^*(\alpha)$  characteristics, each for three different wheel loads  $F_{z,i}$ . The TMeasy implementation in Modelica, see Sect. 2.2, is used as the basis for a virtual tyre test rig. In order to obtain force/torque slip curves  $\hat{F}_x(\kappa)$ ,  $\hat{F}_y(\alpha)$  and  $\hat{\tau}_z(\alpha)$  from the virtual test rig corresponding to their reference values, PID controllers for longitudinal and lateral slip are implemented. They provide a driving torque, a braking torque, and a steering angle enabling the required slip characteristics to be virtually “driven through”. A simulation executable is built from the Modelica coded virtual tyre test rig. Values for the tyre parameters are stored in a tyre parameter file (.tpf) and imported from the simulation executable for each run. DLR’s well-tried software MOPS (Multi-Objective Parameter Synthesis) [7] is used for conducting the parameter identification. MOPS provides a variety of nonlinear optimisation algorithms and different types of cost functions. For the example employed in this paper, a pattern search algorithm is used. The identification task is to find characteristic curves  $\hat{\mathbf{x}} = [\hat{F}_x(\kappa), \hat{F}_y(\alpha), \hat{\tau}_z(\alpha)]^\top$  from the virtual tyre test rig as a function of 52 TMeasy parameters  $\mathbf{p}_{\text{tyre}}$ , [11], such that

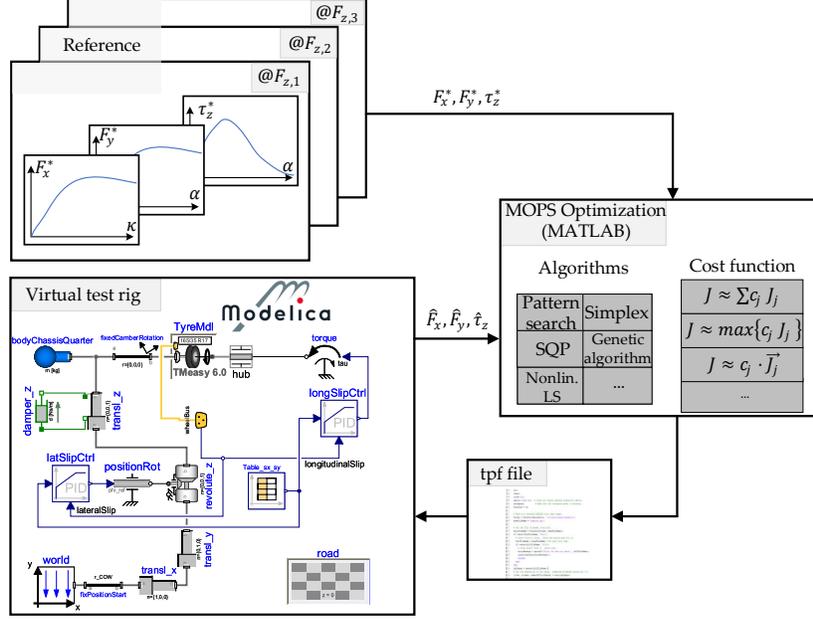


Fig. 2. Overview of the tyre parameter identification framework.

the reference  $\mathbf{x}^* = [F_x^*(\kappa), F_y^*(\alpha), \tau_z^*(\alpha)]^\top$  is optimally fitted by the simulated characteristics. This can be achieved in terms of minimizing the cost function

$$J = \mathbf{c}_w \sum_{k=1}^n \underbrace{\left( \mathbf{x}_k^* - \hat{\mathbf{x}}_k(\mathbf{p}_{\text{tyre}}) \right)^2}_{:= \boldsymbol{\epsilon}_x}, \quad \boldsymbol{\epsilon}_x \in \mathbb{R}^{l \times 1}, \quad \mathbf{c}_w \in \mathbb{R}^{1 \times l} \quad (3)$$

through tuning of  $\mathbf{p}_{\text{tyre}}$ , where  $n$  is the number of discrete time points. The sum of the squared residuals  $\boldsymbol{\epsilon}_x$  is weighted by  $\mathbf{c}_w$  for each characteristic curve  $l$ . Due to the physically interpretable parameters of TMeasy, it is possible to limit the solution space of the nonlinear optimisation problem by formulating corresponding constraints. Thus, only meaningful ranges are considered for the tyre parameters, such as the maximum values of the tyre forces or torques, or the typical curve slopes. For each iteration, the virtual tyre test rig simulations are invoked in MOPS by running the executable after setting modified tyre parameters  $\mathbf{p}_{\text{tyre}}$  in the tpf-file.

In general, it is possible to identify all TMeasy parameters with the help of the presented framework when reference data is available. A simulation based identification of the bore torque parameters could not yet be performed, since currently the necessary maneuver (a loaded wheel rotated about the vertical axis only) cannot be simulated on the virtual tyre test rig. For future investigations, it

is planned to extend the test rig correspondingly. As an alternative, identification based on measured data is performed here and explained in the next section.

### 3.2 Bore Torque Parameter Identification

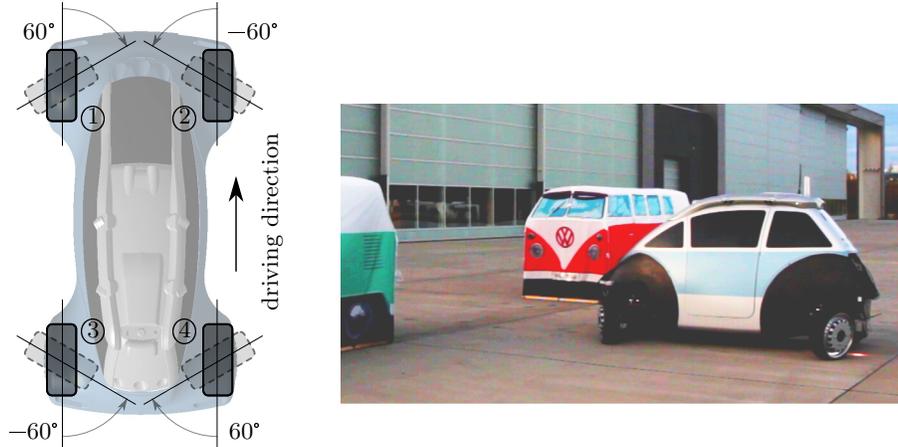
Typically, bore torque characteristics are determined by dedicated experiments with single tyres on specialised test rigs. However, no such data is available to us. Therefore, we tried to exploit own measurements from a real world parking experiment with a unique experimental vehicle. The effective approach is demonstrated in this section.

**Experimental Vehicle and Vehicle Model** The measurement data was taken from a former parking experiment with the ROboMObil – a robotic electric vehicle research platform developed at and run by DLR’s Robotics and Mechatronics Center (RMC). It features four so-called Wheel Robots which are similarly constructed and integrate drivetrain, brakes, steering, and suspension [3]. During the experiments (see Fig. 3), each of them carried a tyre *Nankang 165/35 R17 75V DOT 4307*.

To understand the principle of the performed bore torque related parameter identification, the steering assembly of the ROboMObil is explained in more detail. It is an electromechanical actuator being a fix part of the wheel carrier. The actuator is a unit of a permanent magnet synchronous motor (PMSM) and a harmonic drive gear. Its output shaft is connected to a pinion which meshes with a larger spur gear rotationally fixed to the suspension’s upper wishbone. The steering assembly facilitates steering angles in a total range (left to right limit) of  $\approx 125^\circ$ . Thus, even sideways driving of the ROboMObil or rotating on the spot is enabled. A torque sensor provides measurements of the steering actuator output torque while the steering angle of each individual wheel is the controlled variable.

A high-fidelity validated Modelica model of the ROboMObil is available including a detailed submodel of the steering assembly, see [6]. Together with the TMeasy tyre model, the real vehicle behaviour can be reproduced in a very accurate manner. In this paper, parameter identification focuses on the reliable tyre’s bore torque reproduction based on a real parking experiment, described in the next section.

**Parking Experiment** The specific parking manoeuvre providing the measurement data was performed as follows. At the beginning, called phase I, the vehicle brakes down during longitudinal driving from low velocity to standstill. Standing at rest, all four wheels are steered in phase II to achieve a steering angle of  $\approx 60^\circ$  each, see Fig. 3, to prepare for the following pure rotation of the vehicle. In phase III, appropriate individual wheel driving torques are applied to give the vehicle a quarter turn on the spot. Finally, the wheels are steered to  $90^\circ$  (phase IV) and the vehicle parks sideways. Meanwhile, specific signals such as the rotational wheel speeds  $\Omega_i$ , with  $i = 1, \dots, 4$ , steering angles and torques were logged.



**Fig. 3.** Steering of the four wheels by  $\approx 60^\circ$  during phase II in a top view (left) and the real ROboMObil parking experiment at the same phase (right).

**Identification procedure** The measured wheel speeds and steering angles are set as inputs to the ROboMObil Modelica model, thus implying partial model inversion. This is seamlessly possible in Modelica in contrast to signal-oriented tools, such as Matlab/Simulink. As a result, the simulated wheel motions are identical to the experiments. The steering torques are reproduced involving tyre model parameter dependent forces and (bore) torques as simulated quantities. Apart from using the simulation of the full vehicle model as outlined above instead of a single tyre virtual test rig, the approach used is analogous with Sec. 3.1 and Fig. 2. The cost function  $J$  in (3) here relates to the deviation between measured and simulated torque of the four steering actuators. Since the focus is on bore torque related tyre parameters, and for simplicity, only data is evaluated in the cost function from phase II of the manoeuvre where steering activity and noticeable bore torques appear, accordingly. Phase IV can later be used for validation. In each optimization iteration, the same TMeasy parametrisation is applied to all four tyres. The tuning parameters for the optimization (i.e. the identified tyre parameters) are the torsional stiffness  $c$  and damping  $d$  of the tyre, see Eq. (1), and the bore radius adjustment factor  $\lambda_{RB}$ . The corresponding parameters used in the TMeasy parameter file (\*.tpf) are called CTORS, DTORS, RB\_ADJUST\_1 and RB\_ADJUST\_2. The last two parameters specify the wheel load dependency of  $\lambda_{RB}$  and are characterised by two values at a nominal and a double load which is typical for TMeasy parametrisation.

### 3.3 Identification Results

The parameter identification results are summarised in Table 1. From the results achieved by a first identification run (column *run 1* in Table 1) the two parameters RB\_ADJUST\_1 and RB\_ADJUST\_2 of bore radius stand out. Values close to 2.0

**Table 1.** The bore torque parameters identified during two optimisation runs. The optimisation runs were done for two different `TM_FRICT` values.

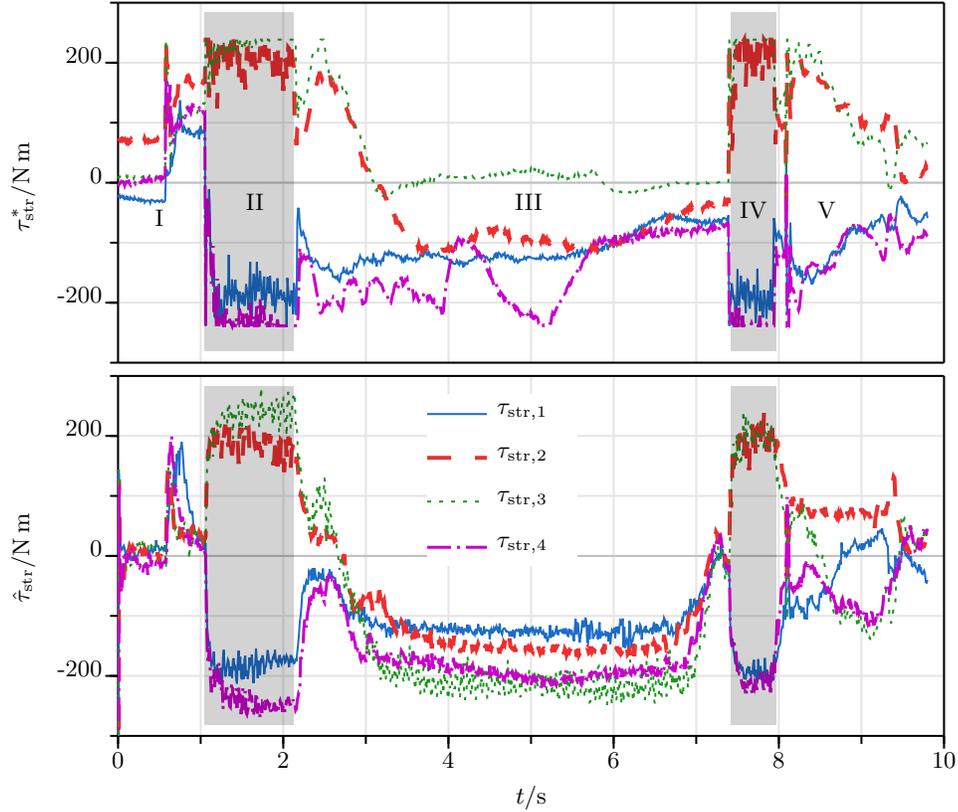
Symbol	TMeasy Parameter Name	Run 1	Run 2
-	<code>TM_FRICT</code>	1.0	1.15
$c$	<code>CTORS</code> / $\text{N m rad}^{-1}$	19550	19155
$d$	<code>DTORS</code> / $\text{N m s rad}^{-1}$	106	280
$\lambda_{RB}$	<code>RB_ADJUST_1</code>	1.99	1.71
	<code>RB_ADJUST_2</code>	1.72	1.17

neither comply with the theory behind nor correspond to previous parametrisation experience. Generally, values about 1.0 are being expected. To obtain more reasonable parameters, Eq. (2) shall be considered. Here, the global derivative  $f_G$  of the generalised tyre force influences the bore torque as well. This quantity depends, amongst others, on the road friction coefficient and, thus, involves yet another parameter of the TMeasy – the local friction adjust factor `TM_FRICT` which admits additional tuning. This single factor allows for scaling of both longitudinal and lateral tyre forces at the same time. Utilising `TM_FRICT`, the characteristics measured on a drum can be e.g. adapted for modelling on a plane ground. Subsequently, the second identification run with `TM_FRICT` = 1.15 – which is indeed a realistic value for such an adaption – eventually leads to more realistic bore radius parameters (run 2 in Table 1) with nevertheless plausible changes of the remaining parameters `CTORS` and `DTORS`.

Finally, using the identified tyre model parameters, the whole parking manoeuvre covering all driving phases is simulated for validation. The real measurements (upper plot) and the simulation results (lower plot) are compared in Fig. 4, with highlighted relevant phases II and IV. Here, the simulated results fit the measurements well. The measured torque signals reveal that the torque limits of the PMSMs are reached occasionally at the rear wheels, i.e. the steering torques  $\tau_{\text{str},3}^*$  and  $\tau_{\text{str},4}^*$ . No limits are modeled in the (inverted) Modelica model of the PMSM. Therefore, this cut-off cannot be observed in the simulated rear wheel steering torques. In the phases I, III and V, the steering torques in parts exhibit significant differences between measurement and simulation. There are several factors which may explain these discrepancies, such as the road irregularities or the road inclination which can even be observed on the photo in Fig. 3.

## 4 Conclusions

A comprehensive parameter identification of TMeasy model for the tyre Nankang 165/35 R17 was performed, with particular emphasis on the bore torque behaviour. The parameter identification was based on torques of four steering motors measured during a real parking manoeuvre of the DLR’s experimental platform ROboMObil, and the approach proves being a viable way to identify



**Fig. 4.** Output torques of the steering assemblies in the experiment (above) and the simulation (below). The wheel indices correspond to Fig. 3, left. The tyre bore torque’s influence is significant only during the highlighted periods.

bore torque parameters. As the identified parameters exceeded expected limits first, another identification run with adapted road friction coefficients leads to plausible results. The identified bore radius adjustment factors indicate a deviation of the Nankang’s contact patch footprint from the round shape presumed in theory. This demonstrates the benefit of the TMeasy which utilises a minimum number of parameters to deliver reliable results.

For future research, the influence of the wheel’s camber angle on the bore torque deployment is of additional interest. For the ROboMObil, the steering axes’ inclination and castor angles lead to high camber angles up to  $10^\circ$  – especially, by design, for the rear wheel robots when steered with  $90^\circ$ . Nonetheless, the influence of the camber angle on the available steering torque measurements could not be observed as the ROboMObil’s steering torques reach the limits of the steering actuators far before the influence observability.

## Acknowledgements

The implementation of the Modelica interface of TMeasy was supported by the ITEA project EMPHYSIS<sup>3</sup> – Embedded systems with PHYSical models In the production code Software.

## References

1. Andres M.: Object-Oriented Modeling of Wheels and Tires in Dymola/Modelica Master Thesis, Vorarlberg University of Applied Sciences, Austria, [http://people.inf.ethz.ch/fcellier/MS/andres\\_ms.pdf](http://people.inf.ethz.ch/fcellier/MS/andres_ms.pdf) (2009)
2. Beckman M. and Andreasson J.: Wheel model library for use in vehicle dynamics studies. The 3rd International Modelica Conference, pp. 385–392, Linköping, Sweden (2003)
3. Brembeck J., Ho L. M., Schaub A. and Satzger C., Tobolar J. Bals J. and Hirzinger G.: ROMO – the robotic electric vehicle. In 22nd IAVSD International Symposium on Dynamics of Vehicle on Roads and Tracks, Manchester (2011)
4. Dempsey, M. and Gäfvert, M. and Harman, P. and Kral, Ch. and Otter, M. and Treffinger P.: Coordinated automotive libraries for vehicle system modelling. The 5th International Modelica Conference, Vienna, Austria, (2006)
5. Drenth E. and Gäfvert M.: Modelica Delft-Tyre Interface. The 8th International Modelica Conference, pp. 8–12, Dresden, Germany, <https://doi.org/10.3384/ecp110638> (2003)
6. Ho L. M.: Application of Adaptive Thresholds in Robust Fault Detection of an Electro-Mechanical Single-Wheel Steering Actuator. The 8th IFAC Symposium on Fault Detection, Supervision and Safety of Technical Processes, (2012)
7. Joos H.-D., Bals J., Looye G., Schnepfer K. and Varga A.: A multi-objective optimisation-based software environment for control systems design. IEEE International Conference on Control Applications and International Symposium on Computer Aided Control Systems Design (2002)
8. Lugner P. and Plöchl M. (eds.): Tire Model Performance Test (TMPT). Veh. Syst. Dyn., 45:sup1, pp. 3–5, <https://doi.org/10.1080/00423110801902673> (2007)
9. Otter M., Elmquist H. and Mattsson S.E.: Multi-domain Modeling with Modelica. In: CRC Handbook of Dynamic System Modeling, Chapman & Hall, pp. 36.1–36.27, (2007)
10. Pacejka H. B.: Tire and Vehicle Dynamics. Elsevier Ltd, Oxford, 3rd ed., (2012)
11. Rill G.: An Engineer’s Guess on Tyre Parameter made possible with TMeasy. The 4th International Tyre Colloquium, Guildford, U.K. <http://epubs.surrey.ac.uk/807823> (2015)
12. Rill G.: Sophisticated but quite simple contact calculation for handling tire models. Multib. Syst. Dyn., 45:2, pp. 131–153 <https://doi.org/10.1007/s11044-018-9629-4> (2019)
13. Rill G. and Arieta Castro A.: Road Vehicle Dynamics: Fundamentals and Modeling with MATLAB<sup>®</sup>. 2nd ed., CRC Press. <https://doi.org/10.1201/9780429244476> (2020)
14. Zimmer D. and Otter M.: Real-time models for wheels and tyres in an object-oriented modelling framework. Veh. Syst. Dyn., 48:2, pp. 189–216, <https://doi.org/10.1080/00423110802687596> (2010)

---

<sup>3</sup> <https://emphysis.github.io/>