

Investigating the Parameterization of Dugoff Tire Model Using Experimental Tire-Ice Data

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ABSTRACT

Tire modeling plays an important role in the development of an Active Vehicle Safety System. As part of a larger project that aims at developing an integrated chassis control system, this study investigates the performance of a 19" all-season tire on ice for a sport utility vehicle. A design of experiment has been formulated to quantify the effect of operational parameters, specifically: wheel slip, normal load, and inflation pressure on the tire tractive performance. The experimental work was conducted on the Terramechanics Rig in the Advanced Vehicle Dynamics Laboratory at Virginia Tech. The paper investigates an approach for the parameterization of the Dugoff tire model based on the experimental data collected. Compared to other models, this model is attractive in terms of its simplicity, low number of parameters, and easy implementation for real-time applications. The relations correlating tire forces with slip ratios were identified by applying zero-phase filtering techniques to the raw test data. Next, an optimization procedure was utilized to extract parameters for the Dugoff tire model from the tire-on-ice drawbar pull coefficient versus slip ratio at certain levels of normal load and inflation tire pressure.

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1. INTRODUCTION

The tractive and braking performance of tires on ice has drawn much attention from the researchers around the world, as it is closely related to the vehicle active safety system. It is important, for example, to know how the Anti-lock Brake System (ABS) will perform for a car running on icy roads. In order to consider the tire performance under such conditions as part of the vehicle control system, an adequate tire model is needed; this effort includes the model development, the parameterization of the model, and the collection of the experimental tire-ice data needed for model parameterization and validation.

A relatively small number of previous studies focused on the mathematic model that predicts the traction performance of tire on ice and could be possibly used on the vehicle control system. A model of traction force in the tire contact patch on ice was proposed by Hayhoe [1] assuming that the contact patch could be divided into two regions: a dry sliding region and a water film region. Based on the same assumption, subsequent models for predicting the traction force of

tire on ice, with higher accuracy and simpler expression relative to the model in [1], were developed by Peng [2, 3]. However, none of those models takes into account the non-uniformity of the pressure distribution in the contact patch, which a modular-structured model, proposed by Bhoopalam [4], does. Furthermore, while the aforementioned models are shown to predict the tractive performance of tire on ice within an acceptable tolerance, none of them account for the lateral dynamics properties of tires, which are critical in predicting the lateral forces. Therefore, such models may not be suitable for use in the vehicle control system that has to control the lateral dynamics. For these control systems, a modified version of the Dugoff tire model could be employed to characterize the lateral and the longitudinal tire forces in the sideslip angle and road friction estimation [5, 6, 7].

Experimental testing of tires on ice can illustrate the influence of operational parameters on the tractive, braking, and handling performance of a tire, and can provide the necessary data for tire-ice interaction models, as well as for the parameterization of

these models. The tire testing machine drum is probably the most common indoor testing machine utilized by the tire industry. Shimizu coated the machine drum in ice so that the variation of the lateral friction coefficient with the slip angle and of the longitudinal friction coefficient with the slip ratio could be tested [8]. Using the same testing facility, Shimizu also explored the effect of various ice textures on the friction coefficient versus slip ratio relation [9]. The influence of operational parameters such as normal load, inflation pressure, toe angle, tread depth, and camber angle on the normalized drawbar pull (named the drawbar pull coefficient) was studied by Bhoopalam via indoor testing of a 16" SRTT tire on ice on the Terramechanics Rig at the Advanced Vehicle Dynamics Laboratory (AVDL) at Virginia Tech [10]. Outdoor tests using the same tire mounted on a truck were also performed to investigate the traction force on ice [11, 12]; it has been noted in this study that a direct benchmarking between the indoor and the outdoor tests results was not possible due to multiple reasons, among which: impossibility to control some of the operational parameters in the outdoor tests, while they were controlled in the indoor tests (e.g., ice temperature and normal load); accurate control of the slip ratio (indoor tests have been performed for very precise slip ratios); vehicle speed (indoor tests can only be performed at low speed).

For the parameterization of a tire model it is important to characterize the dynamic performance of the physical tire first. The complexity of the parameterization process, the associated cost, as well as time needed, increase with the number of tire model parameters. The parameterization processes of three popular tire models: Dugoff tire model, Magic Formula tire model, and FTire model, are briefly discussed here.

Dugoff tire model, with a low number of parameters and acceptable accuracy of predicting longitudinal and later forces, is quite popular for applications involving vehicle control system design [5, 6, 7]. The parameters of Dugoff tire model have physical meanings, and the parameterization could be completed by referring to typical physical values [5] or by using regression techniques to extract longitudinal stiffness and corner stiffness from the tire testing data. Furthermore, the Dugoff tire model is relatively computationally inexpensive, making it a great candidate for real-time simulations or hardware/software in-the-loop simulations.

The Magic Formula tire model [13] has more parameters than the Dugoff tire model, and its parameters don't have physical meanings. Optimization of the tire testing data is needed for the parameterization of the Magic Formula. The main optimization method applied to parameterize the Magic Formula, developed by TNO, uses an optimization technique to fit the Magic Formula parameters using the Matlab toolbox [14]. This method requires starting values of the parameters at the beginning of the optimization. Proper starting values of parameters are not easily accessible for combined a slip condition, for example [14, 15]. Therefore, for this case, the global minimum might not be reached, and, as a

consequence, suitable parameters of the Magic Tire model may not necessarily be obtained using this method. An alternative optimization method based on genetic algorithms could avoid the unfavorable scenario resulted from improper starting values for combined slip condition, as this method doesn't need any starting values to launch the optimization [14].

Compared with the aforementioned two tire models, FTire has a large number of tire design, physical, and modal parameters. Because of this fact, the parameterization process is more complex, including: cleat tests, modal tests, simulations of a Finite Element (FE) model, and optimization techniques. Furthermore, tire design data sheets and simple measurements [16] are also used. Three packages, FTire/calc, FTire/fit, and FTire/estimate, assist users in parameterizing the FTire after the modal test and cleat test are done for an initial and partial parameterization [17]. FTire/calc performs simulations of FE model to partially validate the initial parameterization and to provide a first FTire input file to FTire/fit. FTire/fit tunes the parameters of FTire and does the optimization to minimize the least-squares distance of cleat test measurements and the simulation result of the FTire model on a cleat. Finally, FTire/estimate utilizes the well-validated tire data file and extrapolation techniques to tweak the modal and stiffness parameters of FTire.

As part of the project *Innovative Engineering of Ground Vehicles with Integrated Active Chassis Systems ("Project EVE")*, funded by the European Union Horizon 2020 Framework Program [18], this study conducted testing of a 235/55R-19 all-season tire on ice at Virginia Tech for various combinations of tire pressure, normal load, and slip ratio. The relationship between the drawbar pull coefficient and the slip ratio was extracted from the testing data; the results were further used to study the influence of the design of experiment parameters on the traction efforts of studied tire on ice. By applying a genetic algorithm (GA), the drawbar pull coefficient vs. slip ratio relations obtained from the tire-on-ice testing data are then used to parameterize a Dugoff model for the 19" all-season tire. This tire has been selected since it is the tire selected to be used in the EVE projects. The Dugoff model has been selected due to its relatively small number of parameters required and due to its suitability for real-time simulations. The tire model is intended to be used next for real-time tire inflation pressure control, one of the sub-system control strategies of the integrated chassis control for ground vehicles with off-road ability being developed under the Project EVE.

The paper has the following structure. [Section 2](#) summarizes the key aspects of the indoor tire-ice testing at AVDL used to collect tire-ice data in this study. Next, observations regarding the testing and the presentation of the processed testing data are included in [Section 3](#). Analysis of the testing data has been done in [Section 4](#), discussing aspects of the effects of the inflation pressure and of the normal load on the traction performance of the tire on ice. [Section 5](#) contains the description of the Dugoff tire model and its parameterization method. The paper ends with conclusions on the work conducted, presented in [Section 6](#).

2. INDOOR TESTING

Indoor testing of a 19" all-season tire on ice was conducted at AVDL, Virginia Tech, in February, 2016. A Design of Experiment (DOE) has been prepared as described in the next sub-section. The main objective of the testing was to collect drawbar pull coefficient versus slip ratio data in order to use it to parameterize the Dugoff tire model.

2.1. Design of Experiment

There were three variables considered in the DOE: the normal load applied on the tire, the slip ratio at the tire-ice interface, and the tire inflation pressure. The values of the variable used in the DOE are presented in Table 1. Three levels were used for the normal load on the tire, as well as for the tire inflation pressure. Very small increments (1%) were used for the low range of the slip ratio, and larger increments later. Although we collected such data for larger slip ratio of tires on ice for other projects, the main interest of this project was in the lower slip range, so we limited the top slip ratio at 20%. The toe angle and the camber angle were held at zero throughout the testing. The ambient temperature in the room was around 10°C. The ice temperature was maintained constant at -10°C.

Table 1. Testing variables used in the Design of Experiment.

Testing Variable Name	Number of Levels	Testing Variable Value
Normal Load (kN)	3	5, 6.5, 8
Slip Ratio (%)	20	0, 1, 2, 3, ± 4 , ± 5 , ± 6 , ± 7 , ± 9 , ± 12 , ± 15 , ± 20
Tire Pressure (bar)	3	1.5, 2.5, 3.5

To check testing results repeatability and to ensure the use of consistent data in the parameterization process, each combination was tested for at least 3 runs. An average value among those three runs was then used in the parameterization process. Each combination in the DOE was maintained for 20 sec. during each run, thus providing ample amounts of data points for analysis.

2.2. Testing Setup

The main facility for the testing presented in this study is the Terramechanics Rig at AVDL, Virginia Tech. The Terramechanics Rig, as shown in Figure 1, was developed to study the performance of tires on various surfaces under well controlled conditions [19]. The rig has two main sub-assemblies: a powered carriage and an ice chamber. The carriage moves at a constant speed of 7 cm/s from one end to the other end of the chamber where the ice layer is created. The tire, mounted on the carriage, rotates about its hub axis, powered by a step motor. The tire lateral position, toe angle, and camber angle can be adjusted manually before each test. During each run the tire starts its motion from the home position. By controlling the torque applied on the wheel, positive and negative slip ratios can be

achieved in the tire-ice contact patch, simulating traction or braking. For each run, the tire moves from the home station of the carriage to the front end of the chamber, as seen in Figure 1. While the normal load is held at a preset constant value by its controller, four slip ratios, each maintained for 20 sec., are achieved in each run along the chamber by using a controller to vary the wheel rotational speed.



Figure 1. The Terramechanics Rig at AVDL, Virginia Tech.

The main measurement system for the Terramechanics Rig is a KISTLER P650 force hub. The KISTLER P650 force hub is equipped with transducers that can measure the instantaneous three wheel forces and three wheel moments. The raw data measured is recorded by LMS Test Lab for post-processing.

By controlling the rotational speed of wheel hub, ω , the slip ratio of the tire is controlled based on the Eq. (1) [20], knowing the translational speed of carriage, v_{carr} , and the effective rolling radius of the tire, R_{eff} (obtained beforehand).

$$s = \begin{cases} 1 - \frac{v_{carr}}{R_{eff} \times \omega} & \text{traction mode} \\ -1 + \frac{R_{eff} \times \omega}{v_{carr}} & \text{braking mode} \end{cases} \quad (1)$$

A ladder-value-based software named PicPro is used for programming the controller. The normal load is applied on the tire via two air springs, and the air flowing through the pneumatic flow control valve to the air spring is regulated by changing the control input, the voltage to the flow control valve. By increasing the target value of the input voltage on the LabVIEW interface, the voltage to the flow control valve tracks the target value under the effect of a PID controller, which results in a correspondingly higher normal load on the tire. When the wheel force in the vertical direction measured by the KISTLER P650 system and displayed on the monitor reaches the target value of normal load within a very small fluctuation, the input voltage no longer needs to be increased, and remains unchanged for the coming run of the testing.

