Design and Validation of an ABS and TCS Control Strategy Applied in an Automotive Simulator Using Model-Based Design Methodology

Igor Souza, Lucas Alves Torres, André Murilo, and Rafael Rodrigues Silva

Abstract—**Automotive simulation tools have been employed in various areas of knowledge, especially in the production chain of the automotive industry. The main benefit of these tools consists of reducing the time and product development loops, which directly implies a reduced production cost and improved quality. Thus, the present study aims to use the VI-CarRealTime software widely used in the automotive industry to design and validate ABS and TCS automotive control systems using the Model-Based Design methodology. The simulation results show that the controllers meet the operating requirements well, showing a high correlation when compared to models of a complete vehicle for application in automotive simulators.**

Link to graphical and video abstracts, and to code: https://latamt.ieeer9.org/index.php/transactions/article/view/9517

Index Terms—**Automotive Control Systems, Automotive Simulator, ABS, TCS, Model-Based Design**

I. Introduction

A. Contextualization

AUTOMOTIVE control systems have been increasingly used to improve vehicle safety and comfort, justifying their mandatory use in several countries. Specifically, active safety systems are key in reducing traffic accidents by automatically affecting the dynamic behavior of vehicles. In this context, two important vehicle safety systems can be highlighted: the Anti-lock Braking System (ABS), and the Traction Control System (TCS) [1].

The design of controllers for ABS/TCS systems requires understanding the longitudinal dynamics of vehicles. The process of generating longitudinal forces to accelerate or brake the vehicle is directly linked to the relative slip of the tire concerning the pavement. With an excessive increase in slippage, the vehicle may reach a zone of instability, with a tendency for the wheels to skid during the acceleration process or for the wheel to lock during braking [2]. Therefore, maintaining this slip within appropriate intervals for safety and comfort during a maneuver is desirable and possible by designing controllers based on wheel slip. This principle is the basis for the operation of ABS/TCS control systems.

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In turn, the design of controllers requires a plant model suitable for testing and tuning parameters. The Model-Based Design (MBD) methodology is an efficient tool in the design of control systems [3]. The development of mathematical models for automotive simulation enables the creation of test environments and the validation of controllers under conditions very close to those of real vehicles [4]. In many scenarios, simplified or linearized models around a vehicle operating point are sufficient for describing the dynamics of interest. Thus, simplifying models to focus on the most relevant movements for a given maneuver is of interest for tuning the controller parameters. A satisfactory correlation with the real vehicle must be maintained. To establish this correlation between models and real vehicles, a solution widely used by the industry is the virtualization of vehicular behavior represented by the use of automotive simulators.

Several well-established simulation software programs in the automotive industry can represent a large portion of vehicle dynamics with a high degree of correlation with real vehicles. An automotive simulator widely used by vehicle manufacturers and auto parts suppliers is VI-CarReal Time (VI-CRT) [5]. With this software, the vehicular dynamics can be parameterized, allowing automotive behavior to be simulated under several virtualized operating conditions. Thus, virtual tests can be performed on real tracks, allowing great similarity with the dynamic quantities of a physical vehicle while in a fully controlled and safe environment.

B. Related Works

Many related studies have considered simpler vehicle models for modeling the longitudinal and wheel dynamics of ¼ of vehicles [6]. Other studies have considered both the front and rear axles in addition to the transfer of load for a ½ vehicle model [7]. Several studies have focused on other dynamic effects of the vehicle, in addition to the acceleration or braking performance, vertical and pitching movements, lateral and yaw movements, or even movements in all axes [8]–[10].

Saha and Amrr developed a traction control system using a vehicle model created in CATIA and co-simulated with Adams/Views [11]. Moreover, model-based approaches utilizing tools such as MATLAB/Simulink and the Automotive Open System Architecture (AUTOSAR) play a crucial role in accelerating the development process, from requirement specification to testing and validation [12], [13]. Additionally, the integration of non-functional requirements (NFR) in early design phases has been emphasized as a means to enhance system reliability, particularly in safety-critical automotive applications [14].

Abdullah investigated the enhancement of ABS performance under varying road friction coefficients using proportional controllers [15]. Zhang et al. proposed a quarter-vehicle braking model incorporating a constraint control method based on the Tangent-Type Barrier Lyapunov Function (Tan-BLF) [16]. Additionally, neural network-based approaches have been explored for ABS and TCS controllers. Biju et al. designed a TCS controller utilizing an adaptive radial basis neural network [17], while Vaezzadeh et al. introduced an ABS controller that integrates fixed-time sliding mode control, artificial neural networks, bio-inspired optimization for the reaching law, and a Takagi-Sugeno fuzzy model for friction function approximation [18].

C. Contributions

This study focuses on designing and validating ABS/TCS controllers using an automotive simulator and mathematical models of longitudinal vehicle dynamics. The development follows the MBD methodology, encompassing modeling, design, and validation stages. Compared to the existing literature, this paper stands out from prior studies due to its methodological integration, comprehensive validation of control models, and potential for real-world application. The key contributions are as follows: (i) Integration of MBD framework with VI-CRT for ABS/TCS control ensuring a more accurate correlation between theoretical models and real-world conditions; (ii) Detailed correlation between mathematical models and full-vehicle simulation, enhancing model fidelity and validation robustness; (iii) Provide co-simulation procedure between MATLAB/Simulink environment and VI-CRT allowing real-time testing and tuning, which better aligns with real-world conditions; (iv) Validation of controllers in realistic acceleration and braking scenarios enabling vehicle stability and performance improvements.

D. Outline

The remainder of this article is organized as follows: section II presents the mathematical modeling of the longitudinal dynamics of the vehicle and the MBD methodology; Section III addresses the design of the slip-based control strategy adopted for acceleration and braking; Section IV describes the test conditions of the vehicle model; Section V presents the plant correlation results with respect to the VI-CRT simulation software and controller validation; and section VI concludes this paper and discusses future work.

II. Model-Based Design Methodology

Model-Based Design (MBD) is a framework that centers the development of control system software around functional models. It supports early testing and validation, enabling requirement checks from the project's outset. MBD also allows for automatic code generation, reducing errors and saving development time [13].

MBD is often used alongside the V-Model, a sequential software development process where each phase is completed before the next begins. This approach ensures continuous testing and model verification throughout the development cycle. An overview of the development and testing stages is shown in Fig. 1.

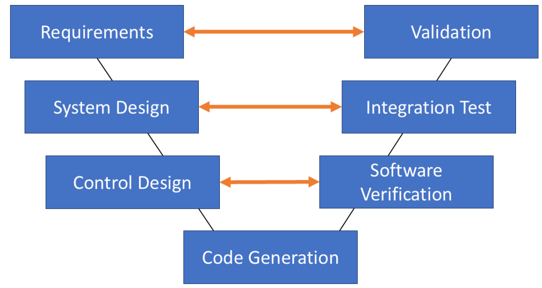


Fig. 1. Workflow of V-Model approach.

The V-Model development process for ABS/TCS control systems begins with defining functional and non-functional requirements. The main objective is to maximize tire-road friction during acceleration and braking by regulating braking (ABS) and both braking and engine torque (TCS). The ECU uses sensor data to calculate wheel slip and decide when to activate control. Mathematical vehicle models are crucial for developing system stability and control.

In the model development phase, vehicle and control models are built in a simulation environment like MATLAB/Simulink. A 3-DOF longitudinal dynamics model represents the plant for ABS/TCS control design. VI-CRT automotive simulation software serves as a reference model to validate this theoretical setup.

During the software design phase, the control models are converted into executable code through automatic code generation for deployment on the ECU or related hardware.

The verification and validation phase ensures the algorithms meet system requirements. Hardware-in-the-Loop (HIL) testing replicates real-world conditions by running the control firmware on the ECU while simulating the plant in real time, helping detect hardware/software integration issues.

Finally, the calibration and acceptance testing phase adjusts system performance to ensure effective real-world ABS/TCS operation.

III. Vehicular Mathematic Model

For acceleration and braking maneuvers in a straight line, the vehicle dynamics involved in modeling the ABS and TCS controls refer to the longitudinal movement and rotation of the wheels. Thus, the mathematical model uses a simplified model of ½ vehicle, as shown in Fig.2. In this figure, F_z denotes the vertical force on the wheels; F_x the longitudinal force; T_t and T_b the tractive and braking torques, respectively; ω the angular speed of the wheel; and u the longitudinal speed of the vehicle. The indices f and r denote the front and rear wheels, respectively.

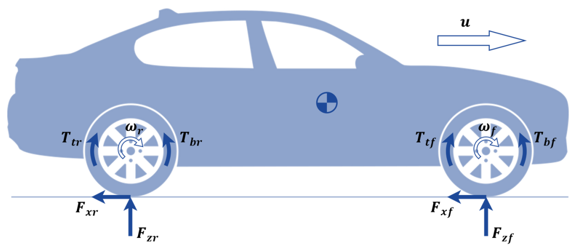


Fig. 2. Diagram of a half-car theoretical model.

A. Longitudinal and Wheel Dynamics

By applying Newton's laws to the resultant force in the longitudinal direction, the following equation for the motion of the vehicle is obtained: $\dot{u} = \frac{F_{xf}+F_{xr}}{m} - gf - \frac{C_a u^2}{m}$. Where m is the mass, g is the acceleration of gravity, f is the coefficient of rolling resistance and the last term is the aerodynamic resistance C_a which corresponds to the drag coefficient.

Similarly, the resultant moment at the axle of the wheels yields the following equation for the movement of the front and rear wheels: $\dot{\omega}_i = \frac{T_{ti}-T_{bi}-F_{xi}\cdot r}{I_w}$. Where r is the radius of the tire, I_w is the inertia of the wheel and i is front or rear.

B. Tire Model

The tires constitute a large portion of the model's performance because they are one of the power sources of the ½ vehicle. With this in mind, Magic Formula, a semi-empirical model that represents the forces acting on tires, was chosen for this study; this model consists of a nonlinear mathematical relationship with parameters obtained experimentally. Therefore, the model is classified as a semi-empirical model and is widely used in industry [19]. The following equations represent the calculation of the longitudinal slip and the longitudinal force generated in the tires according to Pacejka's Magic Formula 2002 version [20].

$$\lambda = \frac{u - \omega_{f,r} R}{u} \tag{1}$$

$$\phi_x = k_x(1 - E_x) + \frac{E_x}{B_x} k_x - \arctan(B_x k_x)) \tag{2}$$

$$F_x = D_x \sin(C_x \arctan(B_x \phi_x)) \tag{3}$$

Where the term k_x that represents the longitudinal slip of the tire equals λ because of tire characteristics that are not considered in this study, B_x is the stiffness parameter, C_x is the shape parameter, and D_x is the peak parameter of the curve. The product of these parameters represents the longitudinal stiffness at the point that the longitudinal slip is equal to zero.

IV. Control Strategy

The ABS/TCS control strategies work similarly. Both developed controls use tire slip as a control variable and aim to maintain tire slip within the desired range to improve vehicle performance. During sudden braking, the ABS actuation system is used, and during acceleration, TCS is used.

The slip is directly related to the coefficient of friction of the pavement, as shown in Fig. 3. The dotted lines represent the slip specification limits for the traction (TCS) and anti-lock braking systems (ABS). These specification limits are used to activate and deactivate each system, depending on the condition of the vehicle. In the example shown in the Fig. 3, the systems are activated when the slip goes beyond the upper slip limit at 0.2; then the system is updated, and for the ABS, the braking torque is removed; and for the TCS, the traction torque is removed. The lower slip limit is 0.1, which is used to re-establish the braking and traction torques to the respective systems.

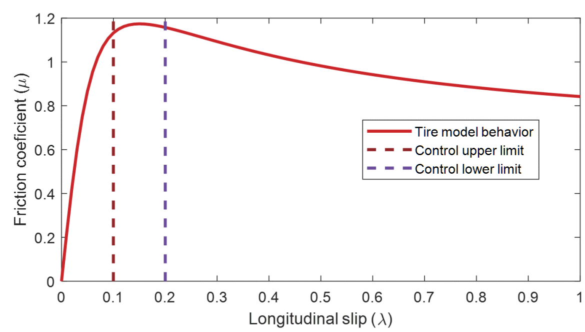


Fig. 3. Friction coefficient behavior concerning the longitudinal slip for the tire model.

A. ABS Controller

The ABS controller modulates braking torque once the brake pedal is pressed. The proposed strategy uses an ON-OFF controller with hysteresis. If wheel slippage exceeds the upper limit, braking torque is deactivated by cutting off the brake hydraulics. If slip is below the lower limit, braking torque remains active. When slip is within the limits, the command is the same as the previous condition.

The slip limits correspond to the region of maximum friction between the tire and road. In this range, the ABS operates in hysteresis mode, rapidly switching the brake hydraulic supply. This creates pressure pulses on the pedal, indicating the ABS is maintaining maximum adhesion. The ON-OFF control law with hysteresis can be formalized as follows:

$$T_b = \begin{cases} T_b, & \text{if } \lambda > l_h \\ 0, & \text{if } \lambda < l_l \\ \text{previous}, & \text{if } l_l \leq \lambda \leq l_h \end{cases} \tag{4}$$

where l_l e l_h are the lower and upper limits, respectively, that define the hysteresis interval for system activation and deactivation.

B. TCS Controller

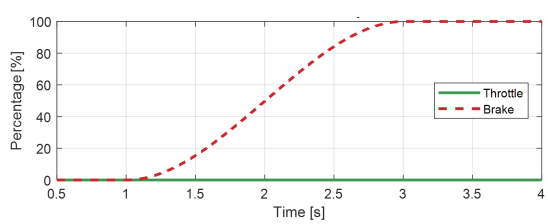
The traction control system (TCS) enhances tire force utilization by preventing slippage during acceleration, improving safety, especially on roads with varying friction coefficients between the tire and road.

This TCS operates as an ON-OFF system with hysteresis. It activates when the longitudinal slip exceeds a threshold and deactivates when slip falls below a lower limit. The activation and deactivation limits are the same. When active, the system reduces tractive torque until the slip returns below the threshold, optimizing wheel adhesion by managing the tractive torque. This control law is similar to equation (4), where braking torque T_b is replaced by tractive torque T_t during acceleration.

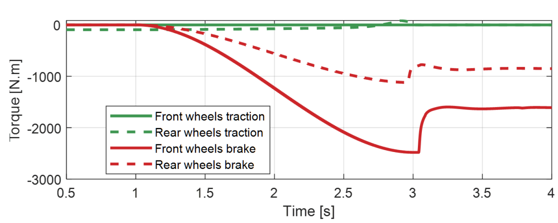
V. Test Scenario

The simulation scenario for evaluating control strategies considers excessive wheel slip during straight acceleration and braking as open loops. Parameters were set for a fixed gear ratio, no steering angle, and progressive acceleration and braking applications. The vehicle follows a straight path, with an acceleration phase followed by a braking phase.

Fig. 4 illustrates the vehicle's brake system activation. The simulation lasts 4 seconds, with the vehicle at 100 km/h. Pedal activation begins around 1 second, and braking continues until the system reaches maximum braking slightly before 3 seconds, maintaining this level until the end of the test. Braking torques on the front and rear wheels are also shown in Fig. 4.



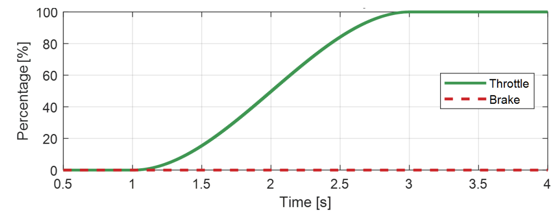
(a) Throttle and Brake inputs.



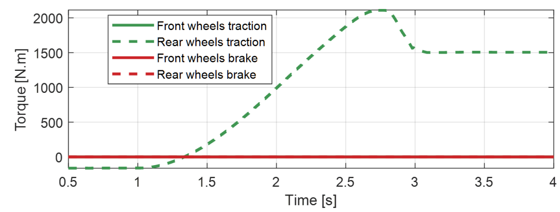
(b) Wheel Torque inputs

Fig. 4. Brake application between 1 and 3 seconds. Front and rear wheels under braking torque actuation.

For the acceleration test, a standard VI-CRT straight acceleration event was used. The vehicle starts at 18 km/h and accelerates in second gear. The accelerator pedal position increases from 0% to 100% between 1 and 3 seconds, with no braking applied. The vehicle in the simulation has rear-wheel drive, as shown in Fig. 5. The simulator is configured to demand maximum acceleration. The selected test track in the VI-CRT is horizontal, flat, and has consistent tire-road friction across its entire surface.



(a) Throttle and Brake inputs.



(b) Wheel Torque inputs

Fig. 5. Acceleration event simulation inputs with an initial speed of 18km/h and constant second gear. Accelerator application between 1 and 3 seconds. Only the rear wheels are under traction torque actuation.

VI. Simulation Results

A. Model Validation

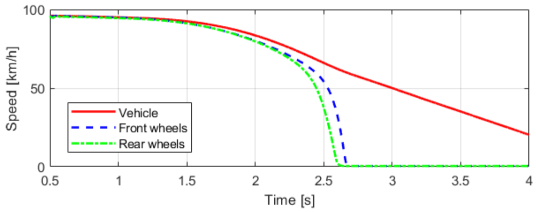
Within the MBD methodology, results must be correlated with a reference model, represented here by VI-CRT. Using the defined test scenario and vehicle theoretical model, an initial simulation without active control provides a baseline comparison between the VI-CRT parameterized model and the one developed in MATLAB/Simulink.

The braking maneuver is first simulated with controls off, and the results are shown in Fig. 6. Vehicle speed and front/rear wheel speeds are displayed. The MATLAB/Simulink model closely matches the VI-CRT benchmark, with R^2 values of 0.99 for vehicle speed, and 0.99 and 0.98 for the front and rear wheel speeds, respectively. Braking distances were 66.96 m for MATLAB/Simulink and 66.88 m for VI-CRT. While slight differences in wheel speeds are observed, the overall vehicle response shows strong agreement between the two models.

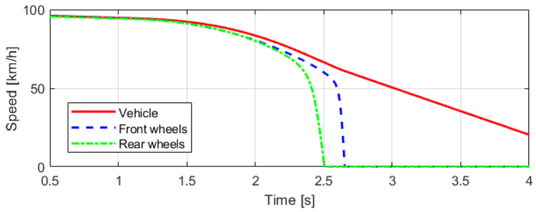
The next test validated the acceleration maneuver, performed with traction control disabled. A strong correlation was observed up to 2.7 seconds after acceleration began, with R^2 values of 0.99 for vehicle speed, and 0.99 and 0.94 for front and rear wheel speeds, respectively, compared to the VI-CRT model. The acceleration distance was 27.05 m for the MATLAB/Simulink model and 27.47 m for VI-CRT.

The most noticeable discrepancies occurred in wheel speeds, contrasting with the braking results. This difference is attributed to the simplified tire model, which only accounts for pure longitudinal dynamics, and to nonlinearities and losses in vehicle components not captured by the 3-DOF model—factors that become more prominent during acceleration.

Despite these differences, final validation can be performed with traction control active. At this operating point, vehicle behavior shifts, allowing the linear assumptions of the 3-



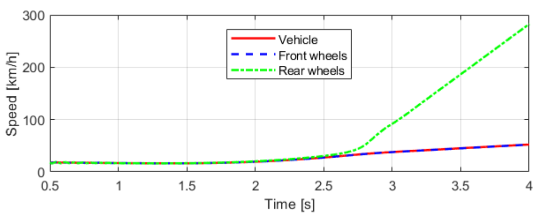
(a) VI-CRT Control Off.



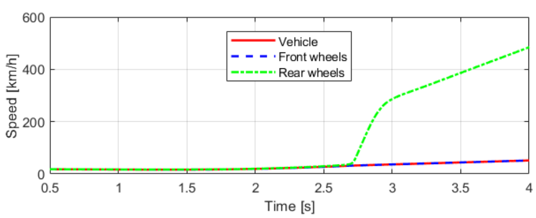
(b) 3-DOF Control Off.

Fig. 6. Correlation between the two models during the braking event without ABS for the validation process.

DOF model to better approximate reality and improving the correlation of dynamic behavior.



(a) VI-CRT Control Off.

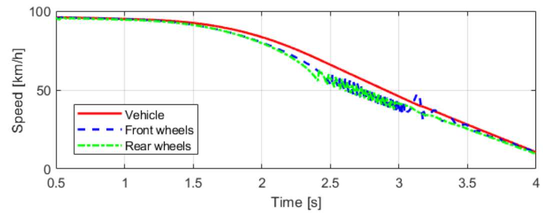


(b) 3-DOF Control Off.

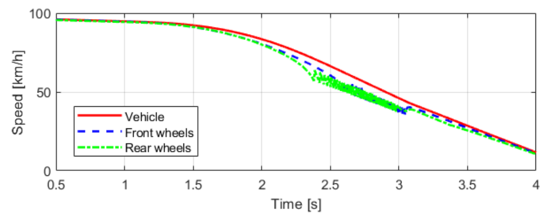
Fig. 7. Correlation of the speeds during the acceleration event without TCS for the validation process.

B. ABS Controller Performance

Once the validation step is completed, the objective is to correlate the behaviors of the controller designed in MATLAB/Simulink applied in the 3DOF simplified model and in the vehicle parameterized in the VI-CRT with all 14 DOFs. An ON-OFF controller with hysteresis was incorporated in the simulation of the theoretical vehicle model, and the limits l_h e l_l were set to 0.2 and 0.1, respectively. The response of this system to the vehicle and wheel speeds in a closed loop is shown in Fig. 8. A high correlation is present between both models for both the vehicle and the wheels, with a R^2 of 0.99 for front and rear wheel speeds compared with the reference model. One can note the switching behavior on the braking pressure of the wheels, allowing them to operate at the maximum possible adhesion between the tire and the pavement. And, as a result, the vehicle had a brake distance of 64.81 m for Matlab/Simulink model and 64.69 m for VI-CRT.



(a) VI-CRT Control On.



(b) 3-DOF Control On.

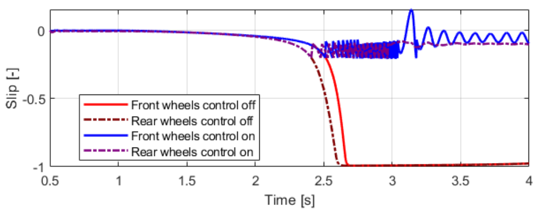
Fig. 8. Correlation of the speeds during the braking event with ABS on.

Fig. 9 shows the longitudinal slip behavior of tire λ again for the two representations and in the scenarios where the ABS is on and off. This figure reveals the difference between the behaviors of the active and passive systems. The ABS clearly controls the slip λ around the interval stipulated in (4), but normal braking is not able to keep the vehicle safe due to sudden speed reductions, leading to $\lambda = 1$, which characterizes wheel locking. This phenomenon can be observed both in the 14DOF benchmark model and in the simplified 3DOF representation.

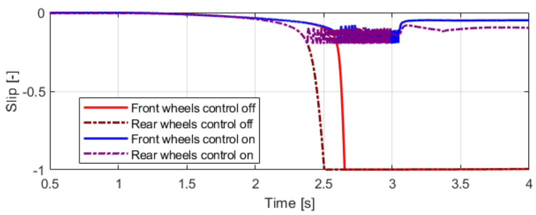
Another important remark consists in the correlation between the two models, which have very similar dynamic behaviors. The greatest difference is observed at the end of the maneuver when the oscillation in the slippage of the front wheel is more significant. However, as the vehicle is a low-pass system, this higher-frequency oscillation is filtered out, causing the vehicle speed to decrease smoothly until the vehicle has completely stopped. For the simplified model, the tire slip acts intensely in the interval between 2.5 and 3 seconds to prevent the wheel from locking, and at the end of the simulation, the tire slip reaches stability.

C. TCS Controller Performance

The same test procedure was adopted to validate the TCS controller. The first scenario of the simulation shows the comparison between the two models with the control activated during acceleration, as shown in Fig. 10. Contrary to what occurred during the validation of the acceleration model, the speed curves of the wheels and the vehicle are very similar. The TCS control adjusted the traction of the wheels in both models and was important for making the resulting vehicular



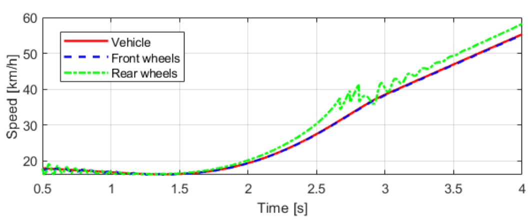
(a) VI-CRT Slip.



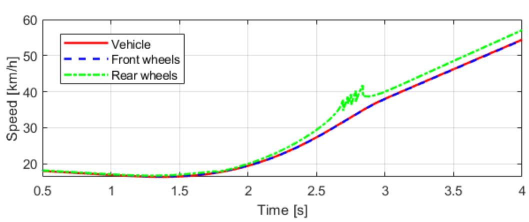
(b) 3-DOF Slip.

Fig. 9. Comparison and correlation of tire slips during the braking event with and without ABS.

dynamics more linear. This explains the greater convergence and correlation of the results, which is quite important, as it indicates that simplified models can capture part of the vehicle dynamics and thus serve as a basis for the design of control systems such as ABS/TCS. The R^2 parameter was 0.99 for the front and rear wheel speed compared with the reference model, and the acceleration distance was 27.75 m for Matlab/Simulink and 27.99 m for VI-CRT.



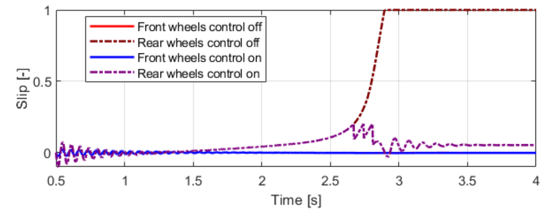
(a) VI-CRT Control On.



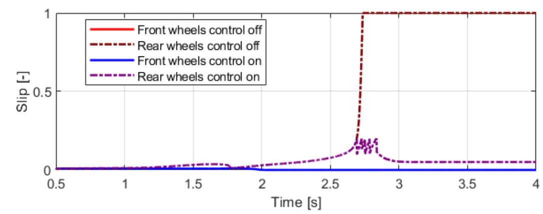
(b) 3-DOF Control On.

Fig. 10. Correlation of the speeds during the braking event with TCS on.

Fig. 11 illustrates the tire slip behavior during the acceleration process, comparing the scenarios with activated and deactivated TCS in the two models. As well as the ABS simulation, without traction control, the vehicle quickly reaches saturation to λ, indicating that the wheel is turning incorrectly. When the TCS is activated, the designed control system can modulate the traction torque on the wheels to ensure maximum adhesion between the tire and the ground while maintaining the tire slip within the predetermined interval. Again, the 14DOF and 3DOF models exhibit similar behaviors for longitudinal slip in all the wheels.



(a) VI-CRT Slip.



(b) 3-DOF Slip.

Fig. 11. Comparison and correlation of tire slips during the braking event with and without TCS.

The main limitations of this study arise from the simplifications in the 3DOF model, which focuses only on longitudinal dynamics, neglecting lateral and vertical effects, as well as suspension and chassis flexibility, which influence weight transfer and traction. Additionally, the tire model assumes a constant road-tire friction coefficient, ignoring variations due to surface grip, weather, and tire wear, which may impact ABS/TCS performance. While the high correlation between 3DOF and 14DOF models confirms the simplified model's validity for initial controller tuning, further validation in full-scale simulations and Hardware-in-the-Loop (HIL) environments is necessary to ensure robustness under real-world conditions.

VII. Conclusions and Future Works

In this study, the results presented showed that through the MBD methodology, behavioral models can be developed with a high degree of correlation with more complex vehicular representations; this approach has become an essential tool for various purposes such as designing control systems. From relatively simple models, the vehicle dynamics of interest with behaviors very similar to that of the model of a complete vehicle were successfully extracted. Notably, dynamic models developed in VI-CRT are widely used in the automotive industry; therefore, when correlated with such representations in this software, they present a very close approximation of the dynamic behavior of real vehicles.

Regarding real-world automotive systems, practical implementation requires validation in embedded systems to ensure effective operation under hardware constraints, addressing challenges like computational efficiency and sensor reliability in real-world conditions. Compliance with automotive safety standards (ISO 26262) is also essential, along with integration into existing Electronic Stability Control (ESC) systems and communication with vehicle ECUs via standard automotive protocols. Thus, this study lays the groundwork for real-world testing to assess ABS/TCS performance under varying road conditions and analyze long-term effects on efficiency and tire wear, reinforcing the practical applicability of the proposed control strategies.

Future work will focus on expanding the model to incorporate lateral and vertical dynamics to validate control strategies through real-time HIL testing, enhancing their applicability to both research and industrial implementations. Additionally, real-time HIL validation will be developed to evaluate control algorithms in physical hardware, bridging the lack between simulation and real-world implementation.

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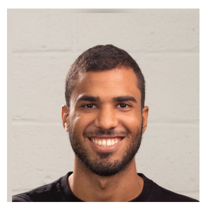

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