VALIDATION OF A MULTIBODY MODEL FOR AN X-BY-WIRE VEHICLE PROTOTYPE THROUGH FIELD TESTING

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Abstract. *Real-time simulations of full-vehicle multibody models are being successfully implemented in more and more cases. These simulations extend the use of multibody models to new fields such as high-fidelity driving simulators and on-board controllers. In order to guide the development of such multibody models, the validity of simulation's predictions must be examined. This paper intends to present and apply the first iteration step of a complete validation process based on the methodology developed to validate the vehicle multibody model of the National Advanced Driving Simulator. For that purpose, an X-by-wire vehicle prototype has been built to generate experimental benchmark data. After that, a self-developed real-time multibody model of this prototype has been programmed. In order to check the validity of this model, a self-developed driving simulator has been fed with the experimental benchmark data, thus enabling the vehicle model to repeat the test maneuvers. Comparison between experimental benchmark data and simulation's predictions are very promising considering that these are the first validation results.*

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1 INTRODUCTION

In the last decade, multibody (MBS) analysis has become a standard to speed up the development process of vehicles [1]. It is worth mentioning that multibody models in the automotive industry have three different purposes that imply different modeling strategies.

The first one, which is the most commonly used, is the vehicle handling analysis, where real-time execution is not required but accuracy and ease of use are essential. Numerous commercial multibody software and self-developed multibody models have been elaborated to carry out this task: for instance a 94 degrees of freedom model has been presented in [2], a control strategy for vehicle trajectory tracking has been introduced in [3], flexible multibody formulations have been employed in [4, 5] and the gap between multibody analysis and classical vehicle dynamics has been studied in [6].

The second purpose is related to real-time simulations. These simulations are used in Human-in-the-Loop (HITL) applications like high fidelity driving simulators or in Hardware-in-the-Loop (HIL) applications for component behavior evaluation. Real-time simulations of full-vehicle have been successfully implemented for example in the National Advanced Driving Simulator (NADS) [7] as well as in several simulators for automotive component evaluation [8–11]. Real-time simulations are not limited to self-developed multibody models. Indeed, the continuous improvement of computer performance has made possible to simulate in real-time full-vehicle multibody models using general multibody commercial software [12]. Recently, the authors of this paper have employed real-time multibody models in automotive state observers, so extending the use of these models [13]. Even if the developed automotive observer does not run in real-time, the research has shown that real-time automotive observers using multibody models will soon be available. Therefore in a near future real-time multibody models could be used on board.

The third and last purpose of multibody vehicle models is associated to crash analysis. Recent works have developed multibody vehicle models to study crash-worthiness [14–16].

When designing a vehicle model, reliability is a major concern. Indeed it is essential to adjust the model's level of accuracy to the application requirements. In the automotive domain, this implies vehicle field testing to gather experimental data in order to evaluate the model's accuracy through comparison. A. H. Hoskins claims that "Without validation of the vehicle dynamics there is only speculation that a given model accurately predicts a vehicle response" [17]. Following this idea, the main aim of this research is to investigate the validity of a real-time multibody model of an X-by-wire vehicle prototype. This prototype has been developed at the Mechanical Engineering Laboratory of the University of La Coruña with a view to its future on board implementation with state observers. This model employs a multibody formulation (developed by this laboratory) that enables the simulation of complex systems to run in real-time with efficiency and robustness [8].

This paper is organized as follows: Section 2 presents the vehicle field testing. In this section, the validation methodology is explained, the vehicle prototype is described and also experimental data for a straight line maneuver are presented. Then, the employed multibody formulation and the self-developed vehicle model are detailed in Section 3. The driving simulator that is used to visualize the maneuvers of this model is depicted in Section 4. The first validation results for the vehicle longitudinal dynamics are discussed in Section 5, and finally, Section 6 presents the concluding remarks.

2 FIELD TESTING USING AN X-BY-WIRE VEHICLE PROTOTYPE

2.1 The validation methodology

Simulation validity is a subjective concept that greatly depends on the objectives of the research. However, the general definition "A simulation will be considered to be valid if, within some specified operating range of the physical system, a simulation's predictions of the system's responses of interest to specified input(s) agree with the actual physical system's responses to the same input(s) to within some specified level of accuracy", proposed by W. R. Garrott [18], will be later applied in this research. According to this definition, it becomes clear that before realizing field testing with the test vehicle, the validation methodology has to be precisely defined. The methodology employed in this research is deeply inspired by the one developed to validate the NADSdyna model of the National Advanced Driving Simulator [18].

A quick summary of the three main phases of this validation methodology is given below. The first phase concerns the experimental data collection through vehicle field testing. The driving maneuvers have to be carefully chosen to cover a broad range of vehicle operating conditions: longitudinal and lateral dynamics, low and high speeds, transient and steady state, etc. Next, to discard any error due to sensor errors, external disturbances, filtering, post-processing, etc, during the measurement of vehicle dynamic responses, the experimental data can not be extracted from only one maneuver of each type. Hence, each maneuver of each type has to be repeated several times in order to average the data of each sensor, consequently increasing the quality of the experimental benchmark data. In agreement with this strategy, the test vehicle must be properly automated to repeat the test maneuvers of interest. The set-up for automatic maneuver repeating on the vehicle prototype developed in this research is presented in detail in Section 2.2. Aside from the improvement of the experimental benchmark data, another interesting advantage of data averaging over several identical maneuvers is determining the uncertainty of the experimental testing and measurement process. According to the definition of simulation validity given in Section 1, this defines the maximum accuracy that the simulation's predictions can reach. During the first phase of this validation methodology, special attention has to be paid to maneuver repeatability. A poor repeatability would be worse than a single maneuver while a good repeatability can greatly improve the experimental benchmark data and also define the error zone. Finally, the last point of this first phase is an extensive post-processing that includes extraction of the desired time interval, offset removal, digital filtering, etc.

The second phase of the validation methodology focuses on the determination of vehicle parameters. Parameters related to the multibody model and also to the subsystems (brake, engine, etc) have to be identified properly. As the vehicle prototype is self-developed, this phase is much easier than for a non self-developed vehicle.

Finally, the third phase consists in repeating the test maneuvers with the vehicle multibody model, in order to compare the simulation's results with the experimental benchmark data of the first phase. The model has been previously configured with the parameters of the second phase, and the model inputs are the control inputs used during the field testing. These comparisons permit the identification of the discrepancy sources between the multibody model and the benchmark data, with the purpose of improving the vehicle modeling and the parameter identification procedures. This iterative process should be repeated until reaching the desired level of accuracy. The first validation results of this research are given in Section 5.

2.2 The X-by-wire vehicle prototype

As previously mentioned, the vehicle model validation is achieved through field testing. It can be performed in many different ways that involve distinct vehicle types. The field testing vehicle can be a scalable vehicle, a commercial vehicle or even a vehicle prototype.

Albeit the dynamics of a scalable vehicle differ substantially from the dynamics of a full scale vehicle, its reduced cost makes it an attractive solution to evaluate MBS formulation efficiency and MBS model accuracy.

The use of commercial vehicles might seem to be the best solution for field testing. However, it carries some important drawbacks such as the difficulty to automate the vehicle for autonomous maneuvers or even the lack of information concerning the vehicle parts. To overcome these difficulties, deep modifications have to be carried out on the vehicle to instrument it and a great amount of identification tests have to be performed on each part. All this leads to an expensive validation process.

Another option is to employ a self-developed vehicle prototype. As a side effect of the self-development process, all the parameters of the vehicle are known. Only a few identification tests for some commercial parts (i.e. engine, etc) must be performed. During the automation of the vehicle, special places and locations for sensors and for the data acquisition system can be included in the design of the prototype at an early stage. As a result development costs have been cut down. In this research, the last solution has been selected [19]. The designed vehicle prototype is a full scale vehicle as demonstrated in Fig. (1).

Figure 1: Self-developed X-by-wire vehicle prototype

The approach of the development phase has been flexibility and low cost as long as the research requirements were complied. When designing a vehicle for automatic maneuver repeating, the first part to be chosen is the engine. In this case, there are two main options: an internal combustion engine or an electric engine. In this research, an internal combustion engine with 4 cylinders and a 2-barrel carburetor assembled to an automatic gearbox transmission has been selected in order to maintain low costs. The vehicle prototype is rear-wheel drive. The use of an automatic gearbox is essential in order to simplify the vehicle automation. The frame has been made from tubes, the front suspension is of double wishbone type, while the rear suspension is of MacPherson type. The model of the 4 tires is Michelin 155/80 R13. The vehicle has also been equipped with a complete Digital Acquisition System (DAS) that gathers sensor data at 500 Hz for each channel and controls the actuators asynchronously.

With a view to maneuver repeating, the vehicle prototype has been provided with several by-wire systems. That is why it is called an X-by-wire vehicle prototype. A throttle-by-wire and a brake-by-wire systems have been set up to control the engine and the braking, allowing to repeat straight-line maneuvers. A steer-by-wire system controls the steering enabling to repeat

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maneuvers involving the lateral dynamics of the vehicle. The choice of both the prototype control inputs and the multibody model inputs are closely dependent. The multibody model inputs can be either identical or not to the prototype control inputs depending on the objectives of the validation.

At this stage of the research, the main objective is to validate the dynamics of the vehicle without including the engine dynamics. For that purpose, the multibody model inputs are the brake pressure, the wheel torques and the steering angle. In addition to the sensors of the by-wire systems, extra sensors are necessary to measure the vehicle dynamics of interest. All the sensors mounted in the vehicle prototype are presented in Table 1.

Measured magnitudes	Sensor
Vehicle accelerations (X, Y, Z)	Accelerometers (m/s^2)
Vehicle angular rates (X, Y, Z)	Gyroscopes (rad/s)
Vehicle orientation angles	Inclinometers (rad)
Wheel rotational angles	Hall-effect sensors (rad)
Brake line pressure	Pressure sensor (kPa)
Steering wheel and steer angles	Encoders (rad)
Engine speed	Hall-effects sensor
Steering torque	Inline torque sensor (Nm)
Throttle pedal angle	Encoder (rad)
Rear wheel torque	Wheel torque sensor (Nm)

Table 1: List of the sensors mounted in the vehicle prototype

2.3 Straight-line maneuver repetitions

When validating a vehicle model, the first maneuvers that must be considered are those involving the longitudinal dynamics of the vehicle. Therefore, the first maneuver, a low-speed straight-line maneuver, has been repeated 7 times on an almost flat test track in the Campus of the University of La Coruña. A topographic survey of the test track is presented in Section 4. At the beginning of the maneuver, the automatic gear was put to go forward and the brake was actuated to held the vehicle steady. Then, the brake pedal was slowly released, allowing the vehicle to start moving. Once the brake pedal was completely released, the throttle pedal was actuated and then released. Finally, the brake pedal was slowly actuated until the vehicle stopped completely. The total distance was 63.5 meters and the maximum vehicle speed was of 23 km/h.

Sensor data have been post processed off-line including scaling, filtering, offset removal, etc. As it is not possible here to present all the experimental data, only the most relevant variables for the considered maneuver are shown. The brake pressure and the throttle angle for the 7 repetition maneuvers are shown in Fig. (2). As shown in this figure, the control input repeatability is very good and could hardly be improved, meaning that the experimental setup of the vehicle complies with the requirements of this research.

Some information regarding the vehicle dynamics is given in Fig. (3). Once again the repeatability is very good, even if the plotted variables are not controlled directly as for the brake pressure and the throttle angle, which are control inputs.
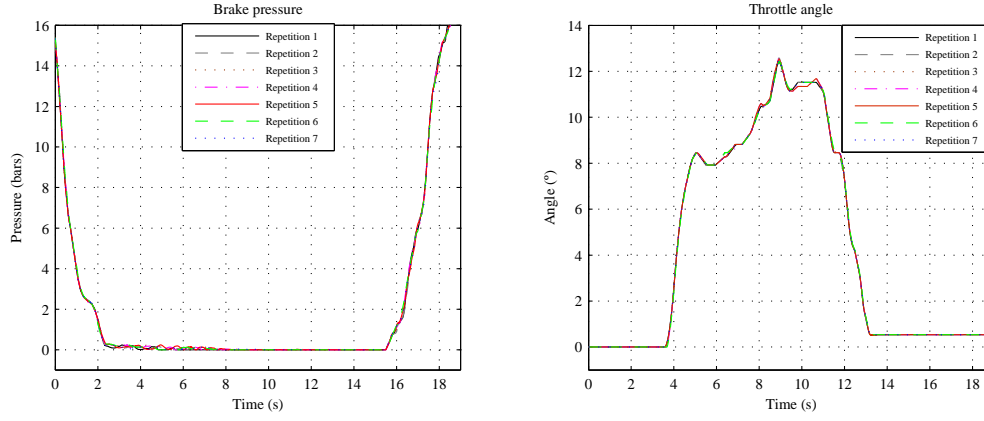
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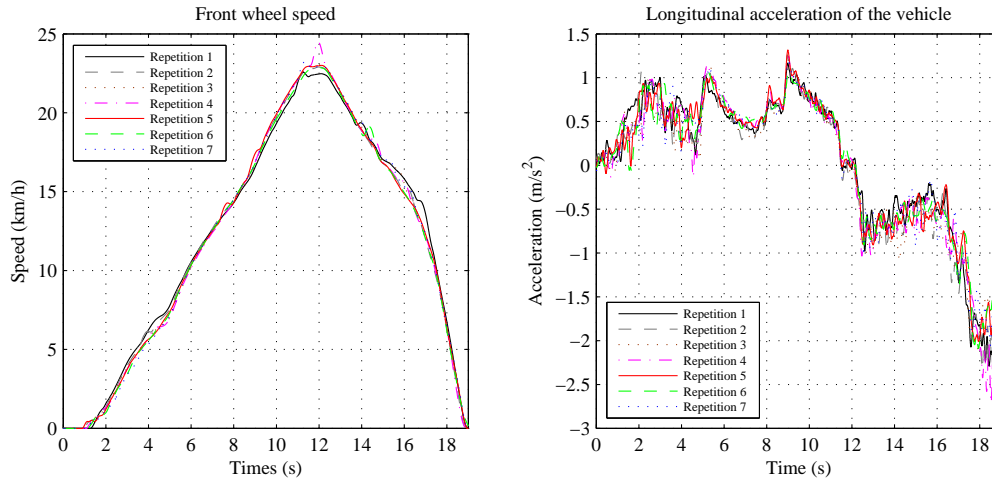Figure 2: Brake pressure and throttle angle of the 7 repetition maneuvers

Figure 3: Front wheel speed and longitudinal acceleration of the vehicle

3 THE MBS VEHICLE MODEL

3.1 The multibody formulation

The multibody formulation used to simulate the dynamics of the vehicle prototype is an index-3 augmented Lagrangian formulation with mass-orthogonal projections [20, 21]. The equations of motion have the following form:

$$\boldsymbol{M}\ddot{\boldsymbol{q}} + \boldsymbol{\Phi}_{\boldsymbol{q}}^{T}\alpha\boldsymbol{\Phi} + \boldsymbol{\Phi}_{\boldsymbol{q}}^{T}\boldsymbol{\lambda}^{*} = \mathbf{Q} \tag{1}$$

where $\boldsymbol{M}$ is the mass matrix, $\ddot{\boldsymbol{q}}$ are the accelerations, $\boldsymbol{\Phi}_{q}$ the Jacobian matrix of the constraints equations, α the penalty factor, $\boldsymbol{\Phi}$ the constraints vector, $\boldsymbol{\lambda}^{*}$ the Lagrange multipliers and $\boldsymbol{Q}$ the vector of applied terms.

The Lagrange multipliers are obtained from the following iteration process:

$$\boldsymbol{\lambda}_{i+1}^{*} = \boldsymbol{\lambda}_{i}^{*} + \alpha\boldsymbol{\Phi}_{i+1} \quad i = 0, 1, 2, ... \tag{2}$$

The sub-index n stands for the time step and the sub-index i refers to the iteration step within a time step. The employed integration scheme is the trapezoidal rule. The corresponding difference equations in velocities and accelerations are:

$$\dot{\boldsymbol{q}}_{n+1} = \frac{2}{\Delta t} \boldsymbol{q}_{n+1} + \hat{\dot{\boldsymbol{q}}}_n \text{ with } \hat{\dot{\boldsymbol{q}}}_n = -\left(\frac{2}{\Delta t} \boldsymbol{q}_n + \dot{\boldsymbol{q}}_n\right) \tag{3}$$

$$\ddot{\boldsymbol{q}}_{n+1} = \frac{4}{\Delta t^2} \boldsymbol{q}_{n+1} + \hat{\ddot{\boldsymbol{q}}}_n \text{ with } \hat{\ddot{\boldsymbol{q}}}_n = -\left(\frac{4}{\Delta t^2} \boldsymbol{q}_n + \frac{4}{\Delta t} \dot{\boldsymbol{q}}_n + \ddot{\boldsymbol{q}}_n\right) \tag{4}$$

Then, the equations of motion are discretized by introducing the difference equations Eq. (3) and Eq. (4) into Eq. (1). The solution of this nonlinear discrete system is obtained using an iterative Newton-Raphson method. Finally, mass-damping-stiffness-orthogonal projections in velocities and accelerations are performed to overcome the difficulties arising from the conditions $\dot{\boldsymbol{\Phi}} = 0$ and $\ddot{\boldsymbol{\Phi}} = 0$, which are not imposed in the solution process.

3.2 MBS model's details

The prototype has been modeled with natural coordinates plus some relative coordinates (angles and distances), which are usually referred to as mixed coordinates. The vehicle model has 14 degrees of freedom: 6 for the rigid-body motion of the chassis, 4 for the suspension and 4 more for the wheels' rotation. The steering has been modeled as a kinematically-guided degree of freedom by means of a rheonomic constraint. Considered forces are: gravity forces, tire forces, forces coming from the suspension system, torques of the engine and of the brake system. Fig. (4) demonstrates a partially exploded view of the CAD of the vehicle prototype with the points and vectors used in the modeling.
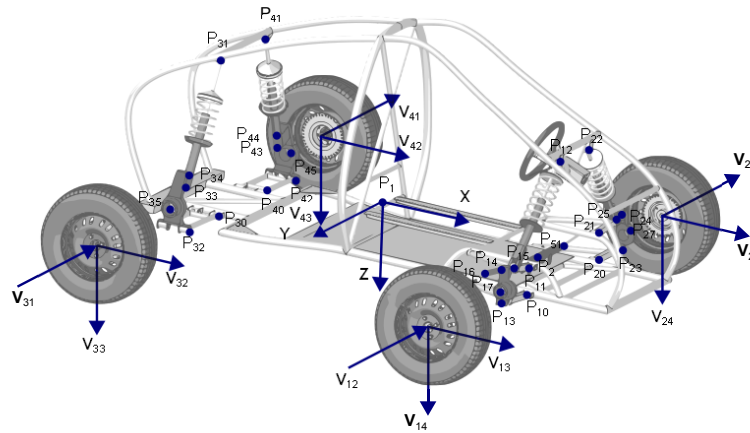

Figure 4: Exploded view of the CAD model of the vehicle prototype

Fortran 2003 has been used to program the whole MBS model. At this point of the research one of the simplest tire models, the basic linearized model, has been employed. The accuracy of this tire model has been considered to be suitable for the first iteration step of the validation methodology. During the next iteration steps, a more accurate tire model will be chosen to improve the fit between the simulation's predictions and the experimental data. The brake model takes into account both friction behaviors: sliding and stiction. During sliding, the braking torque is calculated with the basic following equation:

$$\tau_{brk} = n\mu p A R \tag{5}$$

where n is the number of friction pads, μ is the coefficient of friction between the pads and the disc, p is the braking pressure, A is the brake piston area and R is the radius to the center of the pads.

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4   THE DRIVING SIMULATOR

A self-developed driving simulator, programmed in `C++`, has been setup to make the use of the vehicle model easier. It includes a 3D graphical environment that reproduces the real environment where the test maneuvers have been realized, and a user interface that enables the driver to control the vehicle with any game controller (keyboard, joystick, gamepad, steering wheel...). To display the test maneuvers without latency, the driving simulator communicates in real-time with the vehicle multibody model. To have a better visual interpretation, shapes of the surrounding buildings have been re-created and the road profile in which the test maneuvers have been performed, has been taken into account in the simulator.

The information about the profile has been obtained through a topographic survey of the test track. About three hundred points spaced out approximately every 1.5 meter have been collected. The test track is shown in Fig. (5).
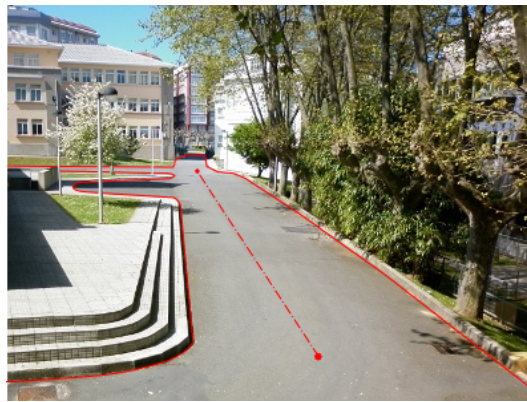

Figure 5: Test track

The 3D scattered data have been interpolated using the natural neighbor interpolation method. Then, using the projections of the points on the "Length-Width" plane, the contour of the 2D point set has been calculated by means of an alpha shape algorithm. Finally, a Delaunay triangulation constrained into the alpha shape has been performed on a regular grid of points. The spacing between the points of the grid is adjustable. Fig. (6) shows the points from the topographic survey and the regularly spaced interpolated points. The vertical scale has been magnified in order to visualize better the test track surface. The triangle mesh of the test track surface is an input of the driving simulator, along with friction and rolling resistance parameters for the tire-road contact on a triangle-by-triangle basis.

To compute the normal reaction forces acting on each tire, in a first stage, the position of the four wheels are tested against the mesh, in order to know if a tire-road collision is taking place. This test also allows to obtain the regions of the mesh that are colliding with each wheel. Each one of those regions is made up of several triangles from the mesh. In a second stage, the normal reaction force (magnitude and point of application) between the tire and the road can be computed, for each wheel, from the orientation and the inter-penetration depth of the stepped triangles. Then, the longitudinal and lateral forces acting on each wheel are obtained using the tire model discussed in Section 3.2.

The multibody simulator has been prepared to reproduce maneuvers previsouly performed by the vehicle prototype. The experimental data recorded during test maneuvers from control inputs and sensors, can be fed into the simulator and passed to the MBS model. Those data must
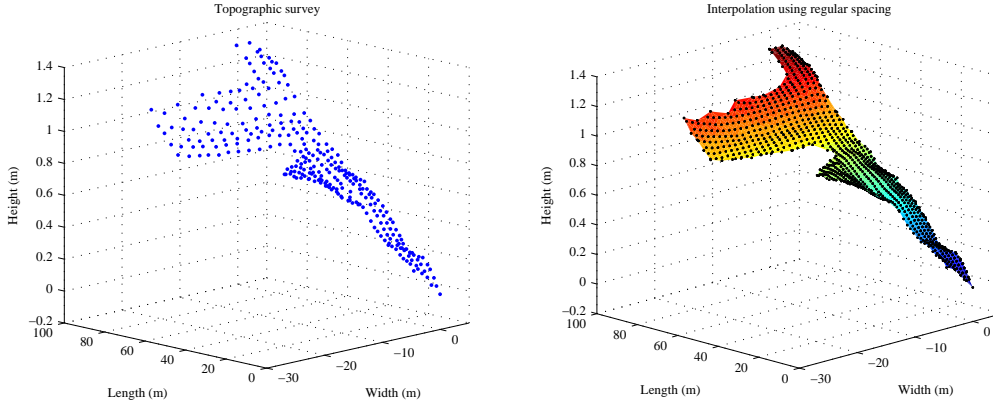
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Figure 6: Topographic survey of the test track and its interpolation

be downsampled or upsampled to address the fact that experimental data are captured with a certain sample rate while the multibody integrator runs at a different time step.

5 FIRST VALIDATION RESULTS

To validate the vehicle multibody model, simulation's predictions and experimental data have to be compared. Therefore, the maneuver of interest must be repeated in the vehicle simulator. For that purpose, the control inputs and the sensor data of the 7 repetition maneuvers have been averaged. For each control input, the average has been input to the vehicle simulator to repeat the maneuver with the multibody model. Next, as mentioned in Section 2.1, aside from the improvement of the experimental benchmark data through data averaging over the repetition maneuvers, it is also possible to determine a confidence interval that characterizes the uncertainty of the experimental testing and measurement process. Here it is supposed that the uncertainty follows a normal distribution, because no other information is available, and also for simplicity's sake. As the number of samples (i.e. the repetition maneuvers) is small, the Student's t-distribution has been employed to calculate the confidence interval as stated in Eq. (6). The interval employed here is a 95% confidence interval with 6 degrees of freedom, as the test maneuver has been repeated 7 times.

$$\bar{x} \pm t^{n-1}_{(1-\alpha/2)} \cdot \frac{S}{\sqrt{n}} \tag{6}$$

where $\bar{x} = \frac{1}{n}\Sigma_{i=1}^{n}x_i$ is the sample mean, $t^{n-1}_{(1-\alpha/2)}$ is the upper $(1-\alpha/2)$ critical value for the t distribution with (n-1) degrees of freedom, $S^2 = \frac{1}{n-1}\Sigma_{i=1}^{n}(x_i - \bar{x})^2$ is the sample variance and n is the sample number. The calculated confidence interval means that a confidence interval in which the true mean is included between the lower and upper bounds, can be found with probability 0.95, for each time step. It is worthwhile pointing out that this confidence interval reduces when increasing the number of samples (i.e. the number of repetition maneuvers) and that it is centered at the sample mean. Fig. (7) shows the rear wheel torque for the maneuver repetitions as well as the mean rear wheel torque and its 95% confidence interval.

Once the sample means for all the inputs of the multibody model have been calculated, they can be input to the driving simulator to repeat the test maneuver with the vehicle model. The inputs employed here are the rear wheel torque and the brake pressure. Fig. (8) compares the experimental results with the simulation's predictions for the front wheel speed and the longitudinal acceleration of the vehicle. The sample mean, its confidence interval and the simulation's
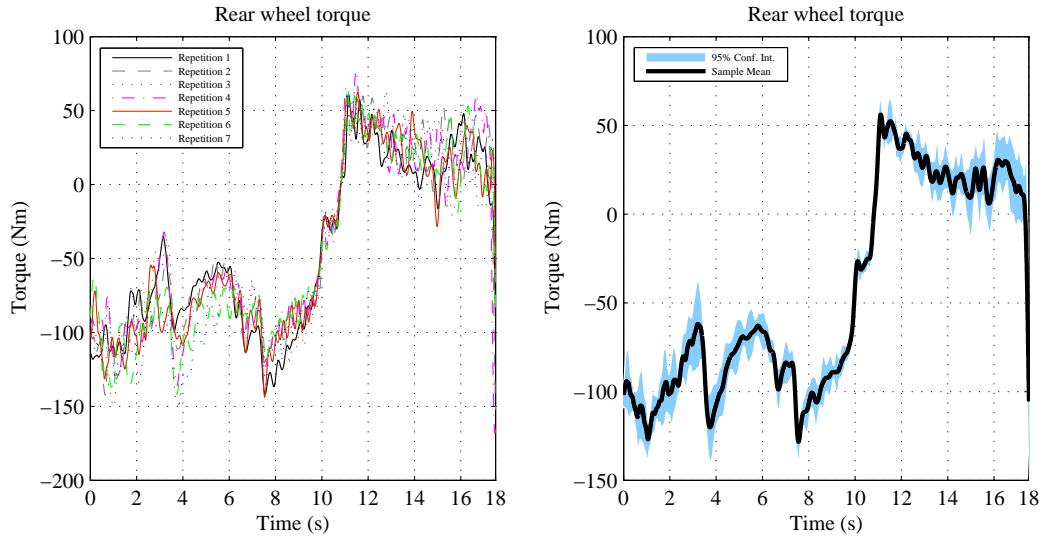
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Figure 7: Rear wheel torque: torque for the maneuver repetitions, mean and confidence interval

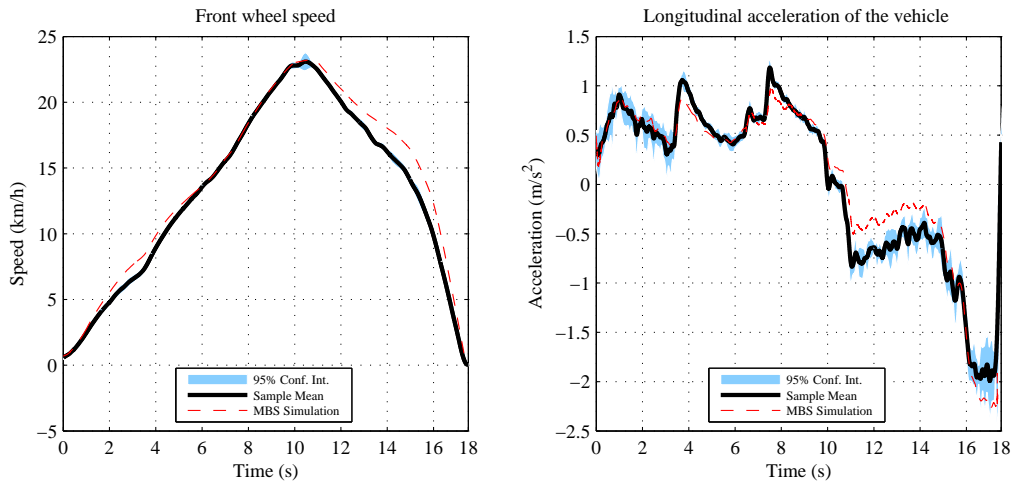prediction are shown for each of these variables.

Figure 8: Sample mean, confidence interval and MBS simulation

Results are very promising, considering that these are the first comparisons between experimental data and simulation's predictions. Many improvements can be found. For example, the employed tire model, being one of the simplest models, should be changed to better match the simulation's predictions. Vehicle parameters (mass, inertias...) and subsystems parameters (brake geometry, engine map...) have to be identified with more accuracy. Once the longitudinal dynamics of the vehicle are accurately matched, maneuvers involving the lateral dynamics will be performed to check the lateral behavior of the vehicle model. This improvement process is an iterative process. For each test maneuver, the correct behavior of the vehicle and subsystems has to be modeled. The real-time vehicle multibody model will be considered valid when the behavior of the vehicle model will agree with the desired level of accuracy, for all the test maneuvers.

6 CONCLUSIONS

This paper focuses on the research on real-time vehicle multibody models. In order to guide the development of such multibody models, the validity of simulation's predictions must be examined. This paper intends to present and apply the first iteration step of a complete validation process based on the methodology developed to validated the vehicle multibody model of the National Advanced Driving Simulator. For that purpose, an X-by-wire vehicle prototype has been built to generate experimental benchmark data. After that, a self-developed real-time multibody model of this prototype has been programmed. In order to check the validity of this model, a self-developed driving simulator has been fed with the experimental benchmark data, thus enabling the vehicle model to repeat the test maneuvers. Comparison between experimental benchmark data and simulation's predictions are very promising considering that these are the first validation results. Future work will focus on the improvement of the vehicle multibody model and its subsystems, on carrying out new test maneuvers and on the improvement of the developed automotive state observers using multibody models.

7 ACKNOWLEDGMENTS

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