Development, validation and RT performance assessment of a platform for Driver-in-the-Loop simulation of vehicle dynamics

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Abstract. Real-time (RT) simulation is a valuable tool in the design and testing of vehicles and vehicle parts, especially when interfacing with hardware modules working at a given rate, as in hardware-in-the-loop (HiL) testing. This scenario is typical when vehicles are equipped with active devices that provide the driver with driving assistance in critical conditions. A specific class of HiL simulation, also known as Driver-in-the-Loop simulation, is a powerful tool to test Advanced Driver Assistance Systems (ADAS) through laboratory tests that actively involve the driver in simulated maneuvers. In this paper, the modular structure of a platform for DiL simulation of road vehicles is described, along with the hardware and the software components needed to enable the interaction of a human user with the simulated environment. The core of the platform is an efficient numerical model for vehicle dynamic simulation, which is developed by using a lumped-parameter formulation and validated by comparison against simulation results achieved with a high-fidelity vehicle model. An evaluation of the computational efficiency is also achieved by assessing the RT performance of the simulation model under a RT operating system.

Keywords: vehicle dynamics; Driver-in-the-Loop; Real-Time simulation; lumped-parameter modelling; model validation

1 Introduction

In the last decades, Hardware-in-the-Loop (HiL) simulation, in which a real electronic control unit (ECU) runs in a closed loop with a Real Time (RT) simulated environment, has been extensively used as a valuable tool to support the design of vehicles and of their control systems. More recently, the development of advanced driver assistance systems (ADAS), which are ever increasingly installed in passenger cars, pushed vehicle engineers to expand the predictive capabilities of the classic

HiL simulation by combination with a driving simulator in a Driver-in-the-Loop (DiL) scheme [5]. The latter simulation environment enables a thorough assessment of the vehicle system performances, since functional hardware tests are complemented by an analysis of the RT driver interactions with the vehicle simulator and with the simulated environment. The main objective of DiL tests is to allow shortening the vehicle development cycle by limiting the need for expensive and time-demanding test drives on a test track or in real road traffic.

Critical for the development of simulation platforms for DiL testing is the availability of numerical models and methods that enable the accurate prediction of the dynamic behavior of the vehicle, subject to the external loads (e.g., the control forces exerted onto the wheels) and to the control inputs coming from the driver (e.g., steering angle, gear shift, position of throttle and brake pedals).

Several dynamic models, based on different formulations, do exist that allow to estimate various vehicle performances in simulated driving scenarios, where the longitudinal (braking or acceleration), vertical (ride and comfort) and lateral (handling) dynamics of the system is excited. High-fidelity Multibody (MB) models enable an accurate prediction of the vehicle dynamic behavior and are typically employed in an advanced phase of the development process, when a virtual prototype of the vehicle that reflects the design choices is created and analyzed for a model-based assessment of the main system-level performances [1, 2]. Detailed MB models are often composed by more than 100 bodies, for which at least the geometry and mass properties are defined, and contain elastic and dissipative force elements with realistic nonlinear stiffness and damping properties, which are introduced to model real components such as shock absorbers and suspension bushings. The simulation results are therefore characterized by a high-level of accuracy, which however is achieved at a huge computational cost that may be un-affordable if RT simulations are to be run.

A lumped-parameter modelling approach can be then used, which is based on the definition of a much more simplified vehicle model composed by few bodies and having a limited number of degrees of freedom (DOFs) [4]. The simplest models that can be used to characterize the vehicle dynamics are the so called *quarter car model* and *bicycle model*, which are both 2 DOF models able to capture the basic vertical and longitudinal/lateral behaviour of a vehicle respectively. An increased level of system complexity and, correspondently, predictive accuracy is achieved by using the *4 DOFs half car model* and the *7 DOFs full-vehicle model*. The former is characterized by a sprung body of non-negligible longitudinal dimension, including inertia momentum along the pitch axis, and takes the bounce and pitch movements of the chassis as well as the vertical displacements of the two unsprung masses into account. In order to analyse the ride behaviour of a passenger car equipped with independent suspensions, the *7 DOFs full-vehicle model* is generally adopted, which uses the bounce, roll and pitch movements of the sprung mass and the vertical displacement of each of the four unsprung masses as generalized coordinates.

In the research work presented here, a *15 DOFs full vehicle model* is developed to enable RT simulations of driving scenarios that involve the longitudinal, the lateral and the primary ride dynamic excitation of the vehicle.

The outline of the paper is the following: Section 2 provides a description of the simulation platform that was developed to enable DiL simulations of vehicle dynamics. The dynamic model used to predict the vehicle response to external control input and forces is illustrated in Section 3. A validation campaign, in which a MB model is used as reference model, is described to demonstrate the capability of the proposed model to predict the vehicle behaviour during various driving manoeuvres. Section 3 shows also the results of a numerical campaign executed to assess the RT performance of the implemented model under a RT operating system (RTOS). Section 4 discusses concluding remarks and future work.

2 Description of the simulation platform

A platform for DiL simulation of road vehicles was developed, which comprises the hardware (steering wheel, gear shifter, pedals, vehicle seat, visual interface) and the software (numerical models of vehicle subsystems and external environment) components needed to enable the interaction of a human user with the simulated environment, as shown in Fig. 1. Specifically, the vehicle system model is based on a modular architecture, in which multi-rate co-simulation between multidimensional sub-component models is implemented under a RTOS.

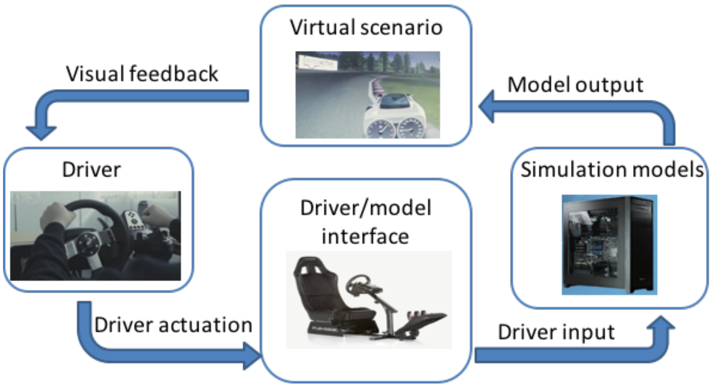


Fig. 1 Schematic of the vehicle simulation platform

The modularity of the platform enables the exploitation of interchangeable subsystem models, so that the DiL tests can be customized based on the requirements and purposes of the simulated driving scenarios. In particular, an adjustable tradeoff between computational efficiency, which is of paramount importance in RT simulation, and predictive accuracy can be reached by implementing scalable-detail vehicle dynamic models, based on different formulations (e.g., multibody, lumped-parameters, hybrid). Without loss of generality, in the work presented here a 15 degrees-of-freedom (DOFs) lumped-parameter vehicle model interacts with functional models of engine, steering system and tires to enable efficient predictions of the vehicle dynamic response to driver inputs (steering angle, braking and driving torque) and to road loads (longitudinal, lateral and vertical forces exerted onto the vehicle at the tire-road contact patches).

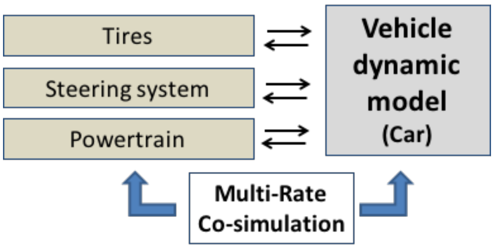


Fig. 2 Software components of the simulation platform and mutual interactions.

3 Description of a 15 DOF vehicle dynamics model

The core component of the simulation platform is a lumped-parameter model of the vehicle, schematically shown in Fig. 3, with the following DOFs:

- the 3 rigid-body rotations (pitch, roll and yaw) of the vehicle body;
- the 3 rigid-body translations of the vehicle body;
- the vertical displacement of each wheel center w.r.t. to the vehicle body;
- the rotation of each wheel around the spindle axis;
- the steering angle of the front wheels.

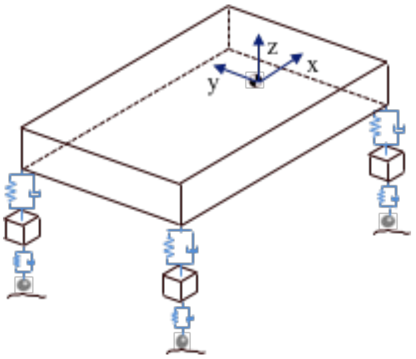


Fig. 3 Schematic of the lumped-parameter vehicle model

The vehicle model described above has 15 DOFs, which allow to describe, at each simulation time and in response to the driver inputs (steering angle, gear shift, throttle or braking effort) the position of the vehicle along the virtual track in the simulated environment and to compute the instantaneous value of the control forces arising at each road-tire contact patch. This is achieved by implementing a set of *Ordinary Differential Equations* (ODEs) governing the dynamic equilibrium of the vehicle chassis (three translational and three rotational equilibrium conditions) and of each wheel (translational equilibrium in the vertical direction and rotational equilibrium around the spindle axis). In the work presented here, this set of ODEs are solved by first-order numerical integration based on the *forward Euler method*. Within the presented simulation platform, for passive vehicle simulations, the dynamic model of the car interacts with the functional models of the other sub-system (tires, steering system and powertrain), with the driver and with the virtual scenario, by exchanging information as summarized in Table 1. In the current implementation, the tire model is based on a spring-damper model and on the Pacejka Steady-State Formula [6] to provide estimates of the vertical and control forces, but more complex formulations (e.g., the Single Contact Point Transient Tire Model) can be employed to capture the transient vehicle behavior.

Table 1. Flow of information between the vehicle model and the other platform components

From→To	***Car***	***Tire***	***Powertrain***	***Driver***
Car		Vertical load, wheel states		Vehicle position & orientation
Tire	Lateral, vertical & longitudinal forces			
Powertrain	Driving/braking torque			RPM, gear shift
Driver	Steering angle		Clutch, gear, throttle, brake	

The platform hardware (steering wheel, gear shift, pedals and monitor) enables Input/Output exchanges between the driver and the different vehicle sub-systems, while the software architecture is based on a Host/Target scheme that improves the system modularity and computational efficiency. The Host component runs in a Windows PC and includes the graphic engine, which enables the visualization of the virtual environment. The Host manages the entire flow of information between the driver and the simulation platform. The Target component, instead, includes the vehicle subsystem models and is run in a dedicated workstation under a RTOS.

4 Model validation and RT performance assessment

To validate the 15 DOF lumped-parameter model a simulation campaign consisting of different virtual driving scenarios has been executed. An estimate of the vehicle parameters was derived by analyzing the geometric, mass and stiffness properties of a high-fidelity multibody model of a passenger car, which is shown in Fig. 4 and which was developed in previous research projects for ride and handling simulations [1]. Such a detailed vehicle model was used as *Reference model* for the validation of the proposed lumped-parameter model.

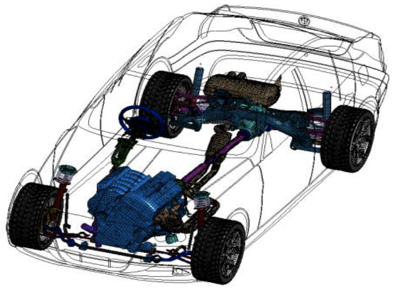
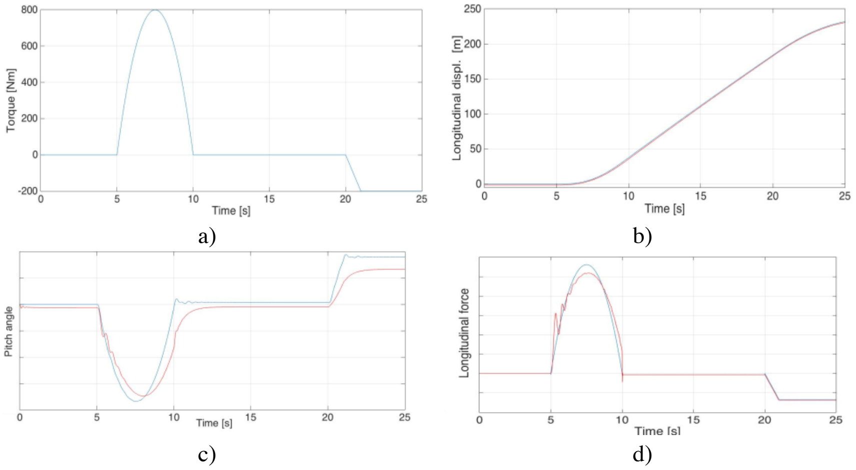


Fig. 4 High-fidelity MB vehicle for ride and handling simulations used as *Reference model*

A first, simple maneuver, consisting of an acceleration phase followed by a braking phase with constantly zero steering angle, was simulated with both the Reference and the proposed model to assess the accuracy of the latter in predicting the longitudinal dynamic response of the vehicle. The time history of the input torque is represented in Fig. 5-a, while Figs. 5-b to 5-d show a comparison of the two models in terms of predicted longitudinal displacement, pitch angle and longitudinal force developed at the rear left wheel. Please note that y-axis values were not always displayed due to confidentiality reasons.



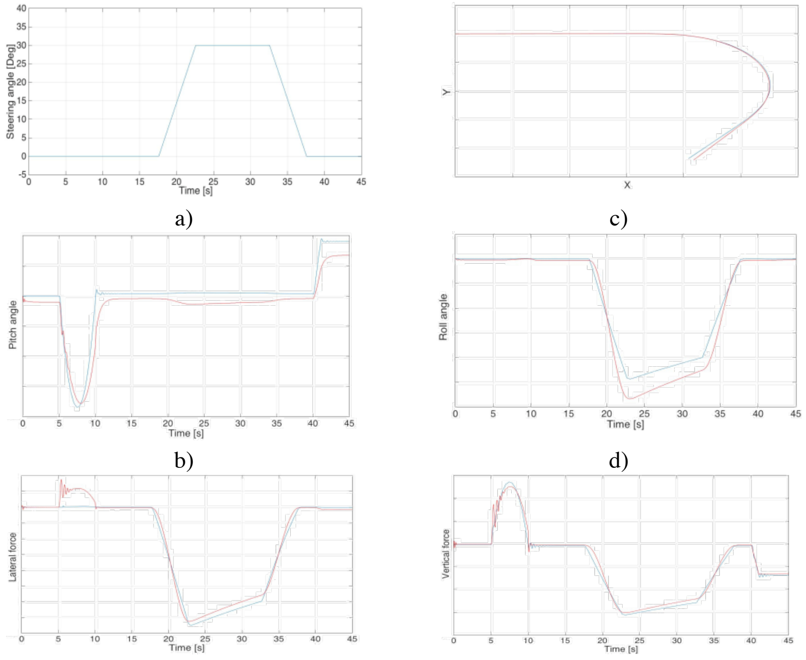
a) b)

c) d)

Fig. 5 Straight line maneuverer: torque input (a), longitudinal displacement (b), pitch angle (c) and longitudinal force developed at the rear left wheel (d) as predicted by the proposed model (blue line) and by the Reference model (red line)

The reported results demonstrate that the proposed model is able to capture accurately the vertical load transfer and the related squat and dive phenomena.

A second maneuver was also simulated, during which the steering input shown in Fig. 6-a was given along with a torque input similar to the one of Fig. 5-a, as to achieve a significant coupled excitation of the vehicle longitudinal and lateral dynamics. Figs. 6-b to 6-f show the vehicle trajectory, along with the time-histories of the pitch and roll angle, as well as longitudinal and lateral forces on the rear left tire as predicted by the proposed and by the reference model.



a) c)

b) d)

e) f)

Fig. 6 Steering maneuverer: steering angle input (a), predicted trajectory (b), pitch (c) and roll angle (d), lateral (e) and vertical (f) forces developed at the rear left wheel, as predicted by the proposed model (blue line) and by the Reference model (red line)

The last step was the assessment of the system performance in terms of hard real-time [3], achieved by setting a simulation case consisting of 100.000 steps. At each step, a driving torque and a steering angle input were sent to the system, from which the state estimates were expected within an imposed response time that was changed between 1 and 0.05 milliseconds. In each simulated case, the number of missed deadlines were computed as a quantitative indicator of the RT performance. With the proposed benchmark, two different configurations were analyzed, in which the Target was run in a dedicated workstation, under either the GPOS GNU/Linux or the Linux-based RTOS Xenomai. The outcome of the analysis is reported in Fig. 7.

In both configurations, the number of missed deadlines is negligible up to a simulation time step of 0.1 milliseconds, while the performance of the GPOS deteriorates at 0.05 milliseconds making the RTOS needed.

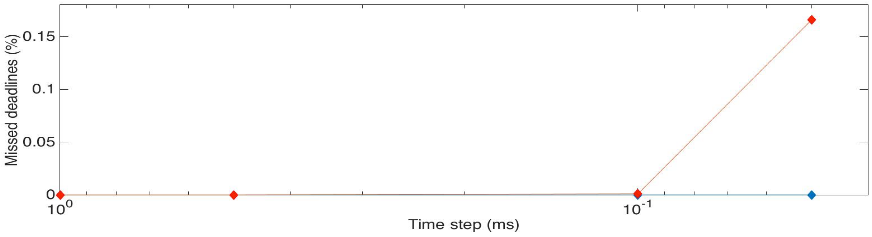


Fig. 7 Number of missed deadlines for the GPOS (red line) and the RTOS (blue line) as a function of the time step

5 Conclusions

In this paper, a platform for DiL simulation of road vehicles was described, which enables the interaction of a human user with the simulated environment. The platform exploits a 15 DOFs lumped-parameter model that allows to predict the vehicle dynamic response to the driver inputs in an efficient but still accurate way, as to enable RT simulations. Virtual tests were executed to demonstrate its predictive capabilities and assess its RT performance.

Next steps are planned and include the integration of the simulator with a motion platform to allow to take into account the human factor, which includes the driver kinesthetic impression and the subjective movement perception. It is of great importance in case of DiL simulation for safety, comfort and ergonomics testing. Further developments of the simulation model are also planned to include mechatronic components and enable DiL testing of ADAS equipped vehicles.

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