Employing Real-Time Multibody Simulation in Driving Dynamics Development

Joost Venrooij, Lucas Rath, Andreas Schultze, Maurizio L'Erario

BMW Group, Development, Driving Experience, address, e-mail: {joost.venrooij, lucas.rath, andreas.schultze, maurizio.l-erario}@bmw.de

Abstract *– This paper describes the employment of real-time multibody systems simulation (RT-MBS) to enable virtual driving dynamics evaluations in a simulator. Three BMW vehicle models were implemented as RT-MBS models. These models and several component variations were evaluated in two driving simulators by expert drivers using the same procedures and maneuvers that are typically used with real-world prototypes. The RT-MBS-models were evaluated by comparing them to two-track models (TT-models) and validated by comparing them with their respective real-world vehicles. The results of these evaluations showed that the RT-MBS-models provide significant quality improvements in the vehicle's response in comparison to the TT-model, both in the lateral and the vertical dynamics. Several relevant driving dynamics phenomena were reproduced more realistically – or in fact, at all – in the RT-MBS-models. Especially the implementation of the flexible car body yields a large improvement. The RT-MBS approach shows the potential to perform significant portions of the DDD process virtually in a driving simulator.*

Keywords: *real-time, multibody, driving dynamics, simulation*

Introduction

Virtualization, i.e., the conversion of real-world hardware, tools, and processes into virtual counterparts, is widely recognized to yield significant cost- and time-reduction potential throughout the industrial value chain.

Automotive OEMs can benefit from virtualization in the vehicle development cycle in several ways, for example by reducing the number of development prototypes, which are notoriously costly in their production and operation. One process within the vehicle development cycle that requires several prototypes and, hence, would benefit from increased virtualization is driving dynamics development[1] (DDD). In practical terms DDD involves the selection and dynamic evaluation of the vehicle body and suspension characteristics (such as dampers, tires, anti-rollbar, elasto-kinematics, etc.) with the goal to obtain a vehicle configuration that meets the driving dynamics requirements in terms of, e.g., comfort, dynamics, and steering.

This paper addresses some of the challenges associated with the virtualization of the DDD process, proposes a product solution, and presents initial results that were recently obtained at Bayerische Motoren Werke AG (BMW).

The challenges of virtualization

The fact that virtual results are less tangible than their real-world counterparts poses a challenge for DDD virtualization. One reason for this is subjective evaluation, which is an essential part of the DDD process: at some point in the development cycle the driving dynamics are to be experienced and subjectively evaluated by expert drivers.

Driving simulators can help to address this first challenge by connecting the virtual world (here: virtual vehicle models) and the real-world (here: subjective evaluations by an expert driver). This, however, poses a second challenge: any model used in driving simulation must run in real-time (RT), i.e., the model must compute within a small and fixed time-step. A model is said to be RT-capable if its real time index (RTI), which is the ratio of the simulated time step over the wall clock time required to calculate the step, is below 1.

A third challenge regarding the virtualization of the DDD process is that it requires highly accurate and detailed simulation models, which allow for a realistic reproduction of the vehicle dynamics and a correct subjective assessment in a driving simulator. A high-quality modelling approach that has established itself across automotive OEMs in the past decades is multibody systems simulation (MBS) (Fischer, 2007), a numerical simulation method in which a

[1] In the context of the current paper DDD is defined to include handling (lateral dynamics) and ride (vertical dynamics) excluding noise, vibration, and harshness aspects.

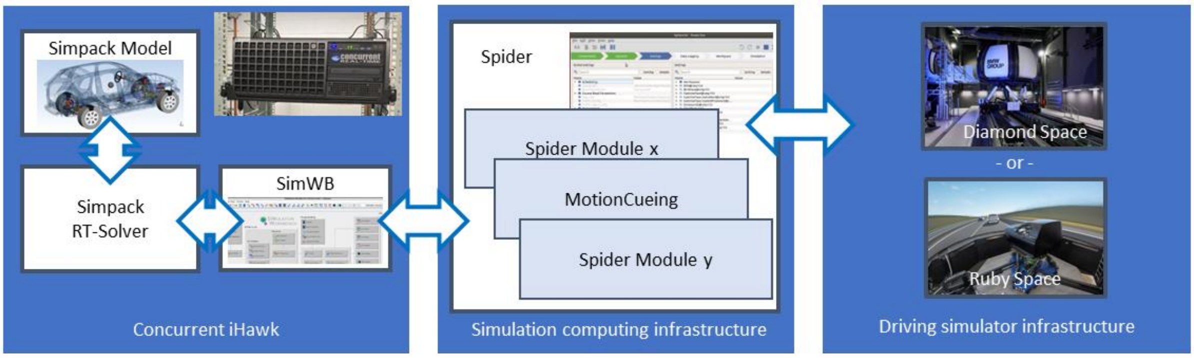

Figure 1: Illustration of infrastructure for real-time multibody simulation

model is composed of various rigid or elastic bodies (Blundell & Harty, 2004). The main benefit of MBS models is that they can provide a high level of physical detail and structural validity, which makes them suitable candidates for use within the DDD process (Mula, et al., 2022). The high model complexity is, however, accompanied by the fact that MBS models are computationally expensive. As a result, MBS simulations are typically time-consuming and often not suitable for real-time applications.

The benefits of virtualization

Besides the benefit of *reducing the costs* of real-world prototyping, which was already mentioned above, there are several other relevant benefits. Virtualization offers the ability to evaluate vehicle models earlier in the process (e.g., before they are built as hardware prototypes) which provides *additional development flexibility*. Furthermore, the execution of virtual evaluations is often *easier and faster* compared to the real-world alternative. Labor-intensive “pit stops”, in which the vehicle is brought into the workshop to exchange components, are replaced by simple parameter changes in the virtual vehicle model. This allows for evaluating various settings rapidly and in quick succession, without significant interruptions. This not only speeds up the process, it also improves the reliability of the evaluation session by reducing waiting times between evaluations. Another significant benefit is the *reduction in logistic complexity* by removing the need to physically bring all required components (vehicle, tires, dampers, etc.) and technical personnel to the same location, at the same time. Finally, the *safety, controllability, and reproducibility* of driving simulation should be noted here as well: evaluations in a driving simulator are generally safer and more controllable than the real-world alternative. For example, evaluations can be repeated as often and for as long as necessary, in identical conditions, and without undesired environmental influences.

In conclusion, virtualization offers additional speed and flexibility in the DDD process while, at the same time, making the process cheaper and more sustainable.

The current paper describes the employment of real-time multibody systems simulation (RT-MBS[2]) to enable virtual driving dynamics evaluations in a simulator. The paper aims to contribute to the exiting literature by 1) presenting an increased level of model fidelity through the combination of flexible structural components with detailed functional component models, 2) providing additional insights on the influence of component variations, and 3) extending the validation of RT-MBS models by comparing the results obtained in the simulator with those obtained on the test track.

Simulation infrastructure

A sketch of the infrastructure is provided in Figure 1.

MBS Software: SIMULIA Simpack

The RT-MBS vehicle models were constructed and simulated using SIMULIA Simpack (Dassault Systèmes, 2023), a general-purpose multibody system simulation software that allows to model and solve non-linear motion of arbitrary systems. The Simpack Solver is complemented by Simpack Realtime, which provides additional I/O and simulation control capability targeted at real-time use-cases for various real-time environments.

Simpack Realtime employs the same models used for non-RT simulation. By adapting the model configuration one can easily transition between non-RT and RT-capable variants.

For the work described in this paper, the Simpack Realtime solver was used with Simulation Workbench (described below).

Real-time hardware: Concurrent iHawk

The real-time simulation was executed using Concurrent iHawk™, equipped with real-time operating system RedHawk Linux (by Concurrent Real-Time). The iHawk is a high-performance Linux-

[2] It should be noted here that the abbreviation RT-MBS is used in the current paper to refer to the real-time capability of an MBS-model. As the RT-capability of a model depends on its configuration the same MBS model may be used in both RT and non-RT applications.

based computer platform for time-critical simulations (Baietto, 2019). In the current project two different iHawks were used with the specifications as provided in Table 1.

Table 1: iHawk specifications

	Ruby-iHawk	Diamond- iHawk
CPU	2x Intel® Xeon ® Gold 6250	2x Intel® Xeon ® Gold 6256
Cores/CPU	8	12
Clock freq.	3.9 GHz	3.6 GHz

Real-time software framework: Simulation Workbench

The real-time software framework, which was used to manage, coordinate, and execute real-time simulations was Simulation Workbench (SimWB, by Concurrent Real-Time). SimWB was used to configure the real-time execution parameters, such as the parallelization, core shielding and core distribution of the simulation processes (the core distribution of the RT-MBS model itself is handled by Simpack's real-time solver). Furthermore, SimWB was used to start the Simpack real-time solver and to monitor the execution time during runtime. Finally, SimWB provided the communication channels between the Simpack model and the simulation software Spider (described below).

Simulation software: Spider

BMW's driving simulation environment Spider (Strobl, 2003) provides a framework for modular distributed real-time driving simulations. Spider allows to initiate, synchronize, and control each component of the driving simulation, from, e.g., the visual scene to the force feedback at the steering wheel. The RT-MBS vehicle model was incorporated through a plug-in in the vehicle dynamics module, which handled the communication with SimWB. The vehicle data obtained from SimWB was routed to the motion cueing module, which provided communication with the control software for the simulator's motion base (see Figure 1). In case of Ruby Space (described below), the manufacturer's motion cueing algorithm (MCA), VI-MotionCueing, was used, which was previously tuned for DDD use cases. In case of Diamond Space (described below), BMW's own DirectMCA was used, which provided a 1:1 reproduction of the vehicle dynamics in all axes, except the longitudinal x-axis.

Driving simulators

The RT-MBS were evaluated on two driving simulators, each simulator was equipped with an iHawk computer (see Table 1). The simulation use-cases that were used are described in the next section.

Ruby Space

Ruby Space (Figure 2) is a 9 Degree-Of-Freedom (DoF) simulator (by VI-Grade), consisting of a hexapod on top of a tripod. The hexapod provides a motion space of ca. +/-0.25m in the x-, y- and z-direction and ca. +/-20° in each rotatory direction. The tripod adds additional workspace of ca. +/-0.75m in the x- and y-direction and an additional +/-25° of yaw. Maximum accelerations are +/-25m/s² in the x- and y-direction, and +/-35m/s² in the z-direction. The available frequency range is approximately 0-30 Hz. Due to low latency and relatively low payload mass, the simulator is particularly well suited for DDD use-cases such as handling and ride. The virtual environment was projected on a 240° projection.

Diamond Space

Diamond Space (Figure 3) is a 7-DoF simulator (by Van Halteren Technologies), consisting of a hexapod on top of a linear rail. The hexapod provides a motion space of ca. +/-1.2m in the x- and y-direction, ca. +/-0.8m in the z-direction and ca. 25° in each rotatory direction. The linear rail adds ca. +/-9m of lateral motion space. Maximum accelerations are ca. +/-10m/s². The available frequency range is approximately 0-15 Hz. Due to the large lateral motion space, the simulator is particularly well suited for DDD use-cases such as lateral dynamics up to the vehicle's handling limits.

Figure 2: Ruby Space

Figure 3: Diamond Space

Methodology

Simulation use-cases

The RT-MBS models were used to evaluate both lateral driving dynamics (e.g., vehicle response, stability, steering feel) and vertical dynamics (e.g., ride comfort, body control) by expert drivers. Each model was evaluated by 2-3 expert drivers. The evaluations were performed using the same procedures and maneuvers that are used with real-world prototypes. Real-world lateral evaluations are performed on a multilane straight test track using maneuvers such as sine waves and step steer at various speeds. The virtual lateral evaluations in the simulator were performed on a four-lane straight road, allowing for these same maneuvers. Real-world vertical evaluations are performed on a road with poor road surface in the Munich area, which is driven at constant speed. The road profile of this road was scanned and virtually reproduced in the simulator for the virtual vertical evaluations. The lateral evaluations were mainly performed on the Diamond Space simulator, the vertical evaluations were exclusively performed on the Ruby Space simulator.

RT-MBS-models of the following BMW vehicle models were developed: 5-series sedan (2017), X5 SUV (2018) and a new vehicle prototype that is currently under development.

The 5-series model was mainly used for initial testing, real-time optimizations, and component evaluations. The X5-model was used to evaluate the effect of stiffness variations in components like the coil spring, jounce bumper and the anti-roll bars. Furthermore, the X5-model was used for the implementation of a flexible car body and the effect of stiffness variations (more details below). Finally, the new prototype model was used as a first productive use-case, providing a preview of the DDD evaluations on the test track that are scheduled for a later date. The results of the virtual prototype-model DDD evaluations will be used as input for the construction requirements for real-world prototypes that are yet to be built.

A common modelling approach for driving simulation models is two-track (TT) modelling. A TT-model can be derived from a (non-RT-capable) MBS-model by replacing physical component models with characteristic curves. This reduces the number of model states, which makes the model computationally faster. To illustrate this: where a typical TT-model contains 16 states, a typical RT-MBS-model contains about 600 states.

In the objective and subjective evaluations, which are described below, the RT-MBS-models were compared with both the associated TT-models and the real-world vehicles. The evaluations were performed using the same procedures and maneuvers that are used with real-world prototypes.

Multibody systems simulation

Using MBS-models for real-time applications requires that the time integration of the equations of motion is always stable and can be completed within a fixed sampling interval (Arnold, et al., 2007). Therefore, the proper choice of the integration method plays an important role in the overall simulation performance. Explicit integration methods are noniterative and very efficient methods but suffer from strong step size restrictions to guarantee stability of the simulation. Implicit integration methods are unconditionally stable but require iterative Newton methods to solve a system of nonlinear equations every time step. To this end, we opted to use a linearly implicit integration scheme, which achieves a very good tradeoff. It exploits a local linear approximation of the equations of motion and provides a fixed number of arithmetic operations per time step while enjoying the same stability properties of the implicit solver.

In addition, algebraic constraints arise naturally due to the kinematic loops present in the vehicle topology. To avoid such kinematic loops loop-closure joints were replaced by very stiff force elements. This allowed us to use an ODE solver instead of DAE, for which we observed a substantial reduction in computational time even though it usually increases the number of DoFs. Another important aspect of having force elements to represent joints is that it allows reproducing compliance (elasto-kinematics) between joints, but it also requires a careful parameterization of these stiff force elements to avoid instabilities or unrealistic dynamical effects. To this end, the time-step size used for all models has been set to 1ms, which provided a stable integration with sufficient accuracy, while still being RT-capable.

Component modeling and integration has been carried out as much as possible using the standard Simpack library. Nevertheless, several components have been integrated into the vehicle model using the FMI interface for model-exchange and co-simulation, which is beneficial for model reuse and interoperability.

The vehicle and its components were parameterized based on static and dynamic measurements, obtained in a variety of test beds on component, subsystem, and system level, allowing for a thorough model validation.

Flexible car body

The structural flexibility of vehicle components, such as the car body, are known to have an important influence on a vehicle’s driving dynamics. Hence, the successful virtualization of the DDD process requires including flexible components in the RT-MBS model.

The flexibility of a body was accounted for in Simpack by including a Flexible Body Input (FBI) file within the model. The starting point for an FBI file is the body's FEM (Finite Element Method) representation, which is then reduced in a process known as condensation. The result is the modal relationship between a set of chosen super elements – which represent the body's attachment points to other vehicle components – together with mass, damping and geometry information, which is then included within the FBI file. Figure 4 shows the BMW X5 with the flexible car body included. Using Simpack's settings to configure the level of detail with which the flexibility of a component is reproduced it is possible to adjust the model's fidelity and its computational load.

The X5 flexible car body model consisted of the body-in-white, the front axle carrier, reinforcement plates and bars. This flexible model was compared with a model without flexible components, i.e., a rigid model. These model variations were obtained through adapting the afore-mentioned flexibility settings, such as the number of modes. A second flexible model variant was generated by exchanging the FBI-file with one where the rear reinforcement bars, located in the car's underbody, were removed from the model. Without reinforcement bars, the lateral stiffness and longitudinal stiffness of the vehicle were decreased by approx. 20% and 21%, respectively. The impact of this "stiffness reduction" on the vehicle's driving dynamics was previously evaluated by BMW expert drivers on the test track. The same evaluation was then repeated in the simulator to validate the accuracy of the flexible body modelling approach (results below).

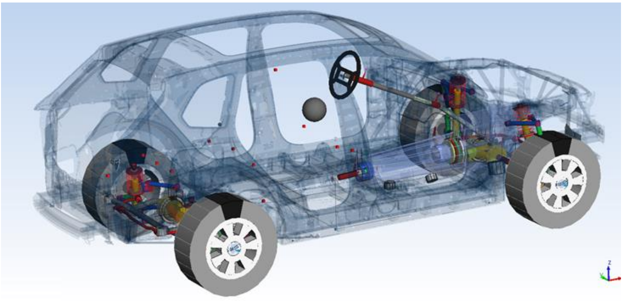

Figure 4: Simpack-model of a BMW X5 with flexible car body

Table 2: RTI-impact of various components (evaluated on Diamond-iHawk)

Component	Variation	RTI difference (approx.)
Car body	Rigid vs Flexible	+26 %
Tire	Basic vs Complex	+6 %
Damper	LUT vs Dynamic	+19 %
Ball-Joint-Friction	Excluded vs Included	+4 %
Engine mounts	Static vs Dynamic	+4 %

Results

Real-time capability

The design and tuning of components such as tires, flexible car body, dampers, engine mounts, jounce bumper, top mounts, and ball joint friction elements was guided by extensive feedback from expert drivers to obtain a proper balance between modelling fidelity and computational load.

Table 2 presents various components variations that were tested. The flexible car body (rigid vs. flexible) was already described above. For the tire modelling a Siemens MF-Tyre/MF-Swift tire model with basic settings (contact method: smooth road, dynamics mode: transient, non-linear) was compared with complex settings (contact method: enveloping, dynamics mode: rigid ring). For the damper a static lookup table (LUT) was compared with a more detailed dynamic model based on local linear model networks (Dessort, et al., 2021). In another component variation a dynamic ball-joint friction model was either activated or deactivated. Finally, the engine mounts were modelled as either static or dynamic. The RTI-impact of each of these variations is listed in Table 2.

Objective evaluations

Objective analyses were used to evaluate the effect of changes to the component models and flexibility settings on overall model quality. The results of these analyses were used in the RTI optimizations. Figure 5 shows the spectral graph of the X5 car body's vertical acceleration for various flexibility settings. The "fully flexible" variant, which contains a large number of modes, provides an accurate representation of the vehicle's flexible behavior but is not RT-capable. The goal of the optimization was to obtain a variant, e.g., by reducing the number of modes, that approximates the fully flexible variant but is RT-capable. It can be observed that the resulting "RT-capable flexible" variant provides a good approximation of the reference and is clearly superior to the "rigid" variant (without flexible modes), especially above 20 Hz.

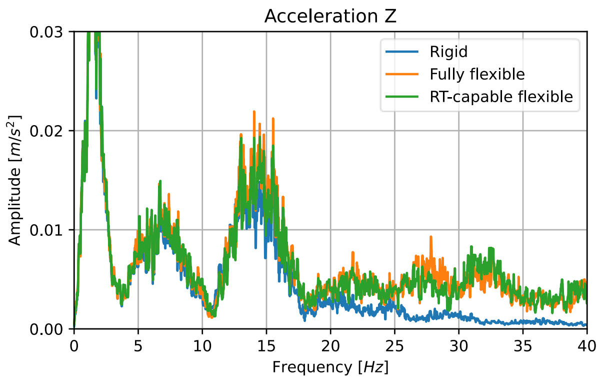

Figure 5: spectral graph of the X5 vertical acceleration at driver seat for various flexibility settings

Subjective evaluations

Subjective comparisons by expert drivers showed that the RT-MBS-models, in comparison to the TT-models, provide significant quality improvements in the vehicle's response both in the lateral and the vertical dynamics. Several relevant driving dynamics phenomena for e.g., the steering feel (such as the initial vehicle reaction) and ride comfort (such as the body progression), were reproduced more realistically – or in fact, at all – in the RT-MBS-models. The subjective evaluations of the component variations showed that components with a large positive effect on model quality are the flexible car body, complex tire modelling and dynamic damper modelling. These three features were amongst the features that were identified as essential for a valid DDD evaluation. Unfortunately, but perhaps unsurprisingly, these features are also computationally expensive (see Table 2). The real-time capability of the RT-MBS-models at the desired fidelity level remains one of the main challenges to be addressed in future work.

The results obtained in the simulator were validated by comparing them with those obtained on the test track. The subjective evaluation of the influence of the flexible car body variants showed a high degree of agreement between the evaluation in the simulator and the test track, indicating that the effect of the stiffness reduction was accurately reproduced by the RT-MBS-model. In both cases the vehicle variation without reinforcement bars showed a comparable worsening of its overall dynamic performance (steering response, roll-angle, reaction delay between front and rear axle). Evaluation of stiffness variations in the coil springs and anti-roll bars, which were first performed in the simulator, were also repeated on the test track. Also here a large degree of agreement in the evaluation results was obtained. These results provide further evidence that DDD evaluations using RT-MBS-models in a driving simulator provides valid and actionable results.

The overall conclusion from these validations is that the RT-MBS-models provide not only superior quality compared to conventional TT-models, but also that such models have the potential to allow for a significant portion of the DDD process to be performed virtually in the driving simulator.

Conclusion

The current paper describes the employment of real-time multibody systems simulation (RT-MBS) to enable virtual driving dynamics evaluations in a simulator. The RT-MBS-models were compared to two-track models (TT-models) and were validated by comparing them with the respective real-world vehicles. The results of these evaluations showed that the RT-MBS-models provide significant quality improvements in the vehicle's response when compared to TT-models, both in the lateral and the vertical dynamics. The results of the validation provided evidence that the results obtained in the simulator are representative for those obtained at the test track.

It should be noted that the validation results are preliminary and a formal evaluation study, executed with a with a larger number of expert drivers, is needed to gain additional insights. Such studies are currently ongoing. Furthermore, the real-time capability remains one of the main challenges in the application of RT-MBS-models going forward. Notwithstanding these limitations, the results obtained with RT-MBS up to this point constitute a significant step forward in the virtualization of the DDD process. They provide solid evidence that RT-MBS models provide a fidelity level which, for the first time, allows for the reproduction of the driving dynamics phenomena which are essential in the DDD process.

Future work will include the development of new vehicle models, the implementation of further model improvements, further real-time optimizations and more elaborate validation efforts.

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