Collaborative Digital Twin Development for Railway Braking and Traction Applications

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Abstract

The paper presents the collaborative development of a digital twin for railway braking and traction applications as part of the ERJU MOTIONAL project. The project's goal is to enhance the efficiency, user-friendliness, and maintainability of European railways through the application of digital twin concepts across nine distinct use cases. Contributing components are shared in a common library as Functional Mock-up Units (FMUs), enabling the creation of digital twins for various applications.

Specifically, this study focuses on the braking and traction use case for virtual validation purposes. The paper details the vehicle dynamics model, control units, and their interfaces, presenting simulation results under diverse adhesion conditions. Additionally, it highlights the potential benefits of digital twins in optimizing railway operations and monitoring system integrity, ultimately enhancing the reliability and efficiency of railway transportation.

Keywords: FMI, vehicle dynamics, railways, digital twin

1 Introduction

Europe's Rail Joint Undertaking (ERJU) (Europe's Rail Joint Undertaking 2022) aims to improve the European railway sector in a public-private partnership. The work presented in this paper is part of the ERJU MOTIONAL project which addresses digitisation of railways for enhanced efficiency, amenity, user-friendliness and maintainability. For this the concept of digital twins (DTs) is applied in nine different use cases. The basic idea is that the project partners contribute components as Functional Mockup Units (FMUs) (Modelica Asssociation Project FMI 2024) to a library which can be combined to DTs for various applications. General aspects of the DT development in EU rail such as use case portfolio, maturity or technology readiness level of the development towards true digital twins with real life objects, availability and dissemination of the models beyond the project and cybersecurity are presented in (Heckmann, Posseckert, and Adusumalli 2025).

This paper describes the current status of the braking and traction (B&T) use case for virtual validation purposes. The proper operation of railway vehicles during traction and braking under different environmental and topographical conditions is the result of the synchronised work of multiple subsystems with a high level of interconnection. Figure 1 shows a scheme of the different components involved in the B&T operation. Developing DTs for B&T is challenging since the actual architecture and number of components change among projects. On top of that, it is common that several providers are involved in the development of the components. These features cause a challenge for the correct integration and commissioning of the B&T system, involving, to a greater or lesser extent depending on the complexity of the project, track testing to finalise its adjustment and ensure correct operation.

In this context, the B&T use case is intended to provide methodologies for the seamless integration of models from different suppliers into a common DT. This would redound to a reduction of errors that need to be corrected during the integration and commissioning phase, with the resulting impact on the profitability of the project as a whole and compliance with delivery deadlines.

The remaining sections of this paper are structured as follows: In section 2 the multi-body model of the vehicle is presented. Section 3 describes the control units and their interfaces. The simulation and results verification of the combined system is presented in section 4. And section 5 relates the work to the digital twin concept. Finally, section 6 concludes the paper and gives an outlook to future plans.

2 Vehicle Dynamics Model

This section describes the models that comprehend most of the mechanical components involved in the B&T DT. As described in Figure 1, the vehicle dynamics model would concern the wheelset and train dynamics, the wheel-rail contact forces, the adhesion level and the track topology.

For the B&T use case, a two car multiple unit for passenger transport is regarded. The vehicle configuration resembles that of a light-rail vehicle-type, which is in the mid-way between tram and metro vehicle-types and whose maximum speed is commonly below 100 km/h. The car bodies are carried by three bogies, i.e. two motor bogies at the ends and a trailing Jacobs bogie at the centre of the vehicle. As usual for this kind of railway vehicles, two stage suspension systems are used to achieve optimal running dynamics and passenger comfort: Rather hard primary suspensions between wheelsets and

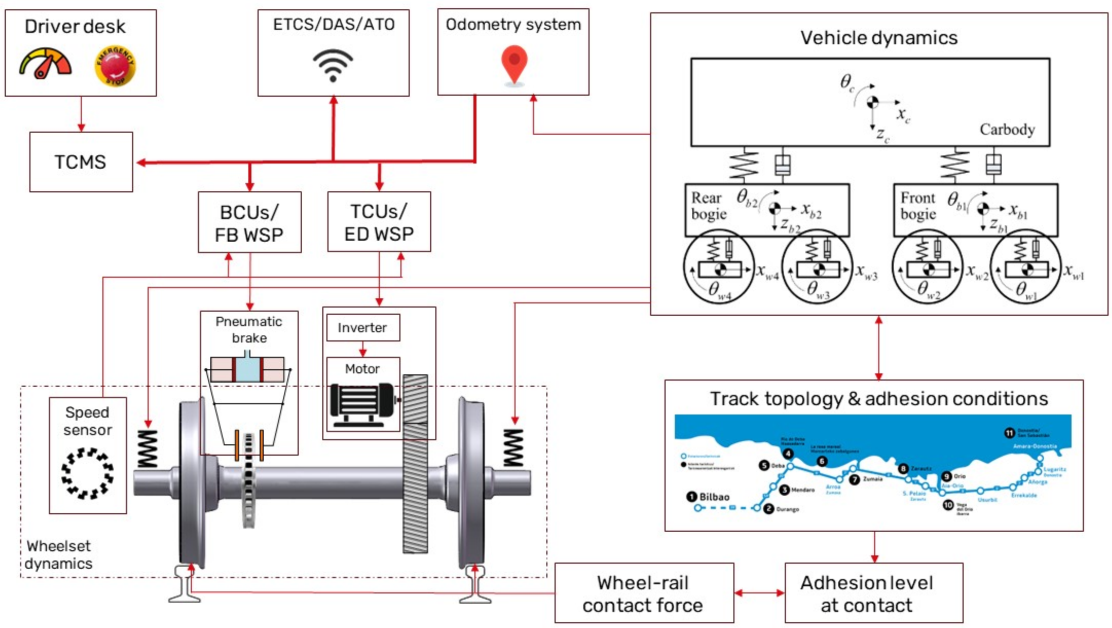

Figure 1. Scheme of the braking and traction system

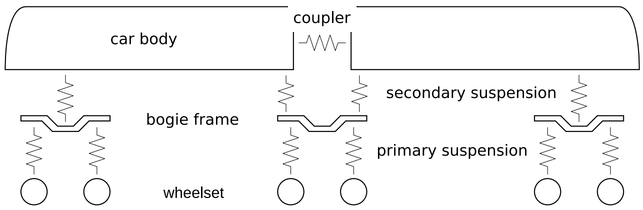

Figure 2. Multi-body structure of the multiple unit vehicle dynamics model.

bogie frames and softer secondary suspensions between bogie frames and car bodies. Completed by a coupler, this structure results in a multi-body system composed of eleven rigid bodies and eleven spring-damper force elements (Figure 2).

Modelica/Dymola using the DLR Railway Dynamics Library (RDL) (Heckmann, M. Ehret, et al. 2019) were chosen for modeling the vehicle dynamics model. In this way it was possible to take advantage of powerful FMU export and sufficient railway dynamics functionality and efficiency. Moreover this setup allowed us to implement the following modifications for the B&T use case.

For analysing B&T phenomena in the scope of this work, lateral, roll and yaw motion of the vehicle are not relevant. As a consequence, these degrees of freedom have been eliminated in the joints of all bodies of the system, resulting in half the number of mechanical dynamic states and accordingly improved computation efficiency. In principle, it would even be possible to consider only half of the vehicle, so that the computation effort of wheel-rail contacts is also halved. However, this has not been implemented so far.

Moreover, an extension of the RDL has been implemented to enable consideration of variable friction coefficients between wheel and rail during simulation. For this a scalar friction scaling factor f_μ has been introduced, which allows to modify the effective friction coefficient of the tangential force law. A common application is to define a lookup table function $f_\mu(s)$ dependent on the longitudinal track position s of the wheel.

The RDL implements different methods for the wheel-rail tangential force determination (Heckmann, Keck, et al. 2014). Since in B&T scenarios high creepage conditions can occur, Polach's method (Polach 2000) is utilised here. It allows to consider variable (e.g. dry/wet) wheel-rail conditions by modification of several parameters A, B, k_A, k_S and μ_0 (Polach 2005). However, so far we just apply the friction scaling factor to the maximum friction coefficient $\mu_0 := f_\mu \cdot \mu_0$ because this approximation is easy to handle and also applicable for other tangential force laws.

Figure 3 shows the block diagram of the vehicle dynamics model. Most of the components are instances of original or modified RDL classes. A linear spring-damper force element with preload has been implemented for suspensions and coupler. Velocity-dependent aerodynamic forces have been added to the RDL car body class. In addition a new brake and propulsion class has been created. It represents a frictional brake and an electric motor acting between bogie frames and wheelsets.

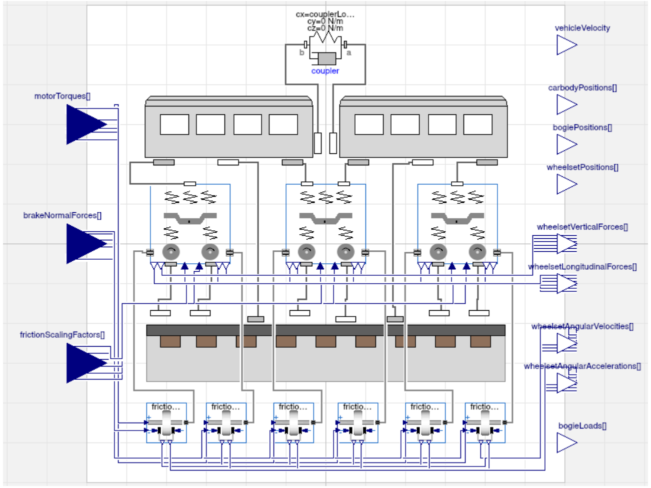

Figure 3. Block diagram of the multiple unit vehicle dynamics model.

At project start it was planned to implement the track as a separate model resp. FMU. However, this concept has been abandoned to avoid confusing and redundant modelling, because defining the track by model exchange would require eight identical track FMUs for all the track joints of car bodies and wheelsets. This is not necessary within Modelica, where the same track is defined as `outer` component of the track joints so that it can be evaluated like a global function. Nevertheless, the architecture of the RDL track implementation has been refactored to enable FMU export for other use cases (Heckmann, Posseckert, and Adusumalli 2025).

All initial conditions, tuneable parameters, inputs and outputs of the model are defined on top level for convenient FMU export. The initial conditions represent the track position and speed of the vehicle at simulation start. There are five scenario parameters, i.e. track data file, car occupancies and friction coefficients of wheel-rail and brake pad-disc, as well as 26 design parameters (mass properties, stiffness and damping values and wind resistance coefficients). Three vectorial input signals are implemented for motor torques, brake pad normal forces and friction scaling factors of the six wheelsets. And finally there are nine output signals, i.e. vehicle speed, track positions of the car bodies, bogies and wheelsets, angular velocities and accelerations of the wheelsets, secondary suspension loads of the bogies and vertical and longitudinal wheel-rail forces of the wheelsets. In the whole these variables form an interface specified for B&T control applications.

A simple test scenario has been used for debugging and testing the model. The vehicle starts at a speed of 10 m/s. From 5 to 10 s of simulation time, a trapezoidal motor

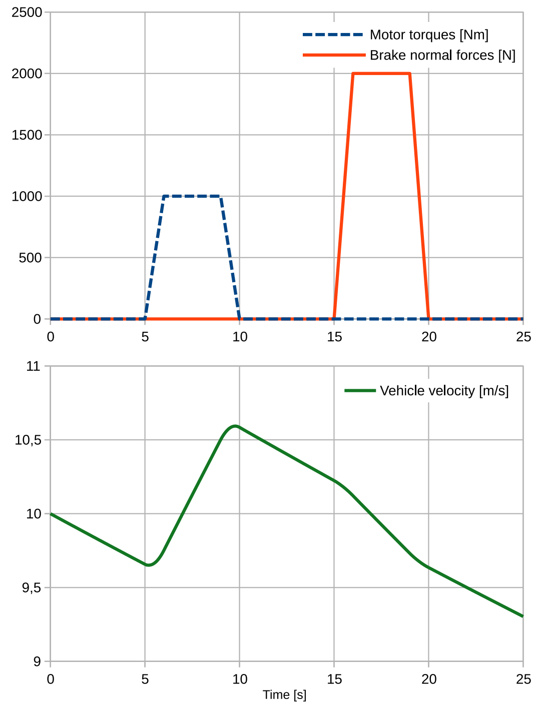

Figure 4. Motor torques, brake pad normal forces and resulting vehicle speed of the test scenario.

torque of 1000 Nm is inputted to the wheelsets. Analogously, a brake normal force of 2000 N is applied from 15 to 20 s. In Figure 4 the inputs and the resulting longitudinal velocity of the vehicle are plotted. During phases without driving torques, the speed decreases slowly due to air resistance forces. When the motor torques are active, the vehicle accelerates, and during braking deceleration increases.

3 Control Model

The control module mainly concerns the description of the logic involved in the B&T operation. Three main functionalities are due to the control module:

- Setting the effort command and operation mode by interpreting the manipulator signals.
- During braking, sharing out the efforts in the most suitable way among the electrodynamic (ED) and friction brake (FB) actuators. This functionality is known as 'blending'.
- To prevent that effort demand exceeds the available adhesion, which involves that maximum admissible longitudinal contact force is about $\mu_0 N$, where N is the normal contact force. This functionality is known as WSP, which stands for wheel-slide/slip protection depending on whether the vehicle is braking or gaining traction, respectively.

As regard to Figure 1, the components concerned by the control module are Traction and Brake Control Units

(TCUs and BCUs, respectively) and Train Control Management System (TCMS). The ETCS (European Train Control System), DAS (Driver Advisory System), ATO (Automatic Train Operation) and the odometry system are not considered in this DT, since they are not core elements of the B&T operation, however, their implementation based on an FMU approach is feasible. The driver desk is highly simplified.

The control architecture is shown in Figure 5. It consists of two TCUs placed at the motor bogies, and three BCUs, one per bogie. The TCMS recieves the driver command and sets the data bus of the vehicle from which the TCUs and BCUs receive the command, read the state of other components and publish their own data. Data communications are compacted in buses signals, which allows to define as many variables as necessary with different data types and sizes without changing the model structure.

In the following subsections, the minimal units describing TCMS, TCUs and BCUs are detailed and their output buses defined. These units are coded in Simulink and subsequently exported as standalone FMUs. The models highly simplify both functionality and included number of variables. However, the overall concept and approach remains valid and further development can effortlessly include more sophisticated or even the actual onboard code.

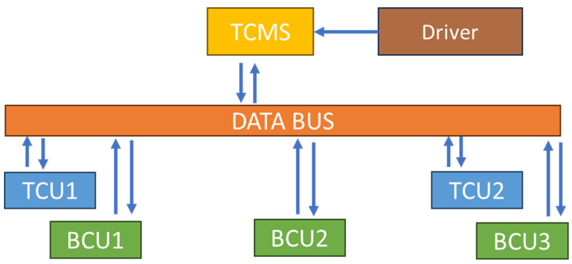

Figure 5. Control architecture of the vehicle

3.1 TCU

TCUs (Traction Control Units) are responsible for controlling the ED actuators (motor) for both ED braking or traction. Moreover, they implement the ED WSP logic. Each TCU publishes a data bus containing four variables included in Table 1.

The TCUs receive the traction or braking demand from the TCMS and calculate how much ED effort they can perform taking into account two main limitations: the effort vs. speed curve of the motor and the available adhesion due to the contact conditions and the normal loads on contact. The resulting effort is the so-called EffANoWSP, which is the effort before WSP control.

Subsequently, they measure the angular velocity of the wheels and, by comparing it with the vehicle speed, estimate whether wheel sliding/slipping is occurring due to degraded adhesion conditions and, in that case, they correct effort. The effort to be applied after WSP correction is denoted as EffA.

Variable name	Unit	Description
EffANoWsp	[N]	Bogie effort before WSP
EffA	[N]	Bogie effort after WSP
b_WSP	[Boolean]	WSP control is acting
b_ED_Ok	[Boolean]	ED is operative

Table 1. TCU data bus variables

3.2 BCU

BCUs (Brake Control Units) are responsible for controlling the FB actuators. Moreover, they implement the pneumatic (or hydraulic, depending on the FB pressure system) WSP logic.

BCUs may act only during braking. The blending strategy seeks to prioritize the ED effort to maximize energy recovery and BCUs may have a small contribution to the total braking effort when adhesion conditions are good in normal braking modes. However, under degraded adhesion conditions, emergency brake mode, or in the presence of failing TCUs, the BCUs will play an important role in the braking operation.

BCUs in trailing bogies are expected to act anytime adhesion conditions are poor due to the TCMS activating low-adhesion mode. However, the blending strategy normally minimizes the actuation of BCUs in motor bogies.

The BCUs read the braking effort demanded by the TCMS and the effort performed by the TCUs and, accordingly, they calculate the braking effort deficit. By measuring the normal load on each bogie they estimate the available adhesion and share the effort among BCUs. In the studied vehicle, only the BCU in the trailing bogie will normally act unless some of the TCUs are failing.

Finally, BCUs also read the wheelset angular velocities and by comparing them with the vehicle speed they decide whether WSP correction is to be applied for avoiding the wheel blockage, which would result in wheel flats. The variables published by the BCU in the BCU data bus are included in Table 2.

Variable name	Unit	Description
WEIGHT	[kg]	Weight on the bogie
FB_REQ	[N]	Requested FB effort
FB_APP_WSP	[N]	FB effort after WSP
FB_AVAIL	[N]	Available FB effort
b_WSP	[Boolean]	WSP is acting
b_FB_Ok	[Boolean]	FB is operative

Table 2. BCU data bus variables

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Variable name	Unit	Size	Description
TRC_BRK_DEM	[Integer]	(1×1)	Traction/Braking demand
NB_ED_AVAILABLE	[Integer]	(1×1)	Number of TCUs available
NB_FR_AVAILABLE	[Integer]	(1×1)	Number of BCUs available
TRAIN_WEIGHT	[kg]	(1×1)	Weight of the train
TRAIN_WEIGHT_ROT	[kg]	(1×1)	Weight of the train including rotational mass
SPEED	[m/s]	(1×1)	Vehicle speed
v_EffA	[N]	$(1\times$ TCUs)	Applied effort per TCU
v_EDOk	[Boolean]	$(1\times$ TCUs)	TCUs availability
v_EffANoWSP	[N]	$(1\times$ TCUs)	Applied effort per TCU before WSP
v_ED_WSP	[Boolean]	$(1\times$ TCUs)	WSP limiting ED effort per TCU
v_FBR	[N]	$(1\times$ BCUs)	Requested FB effort per BCU
v_FBA	[N]	$(1\times$ BCUs)	Applied FB effort per BCU
v_BOGIE_WEIGHT	[kg]	$(1\times$ BCUs)	Vertical load per BCU
v_FBAVAIL	[N]	$(1\times$ BCUs)	FB available effort per BCU
v_FBOk	[Boolean]	$(1\times$ BCUs)	BCUs availability

Table 3. Vehicle data bus variables

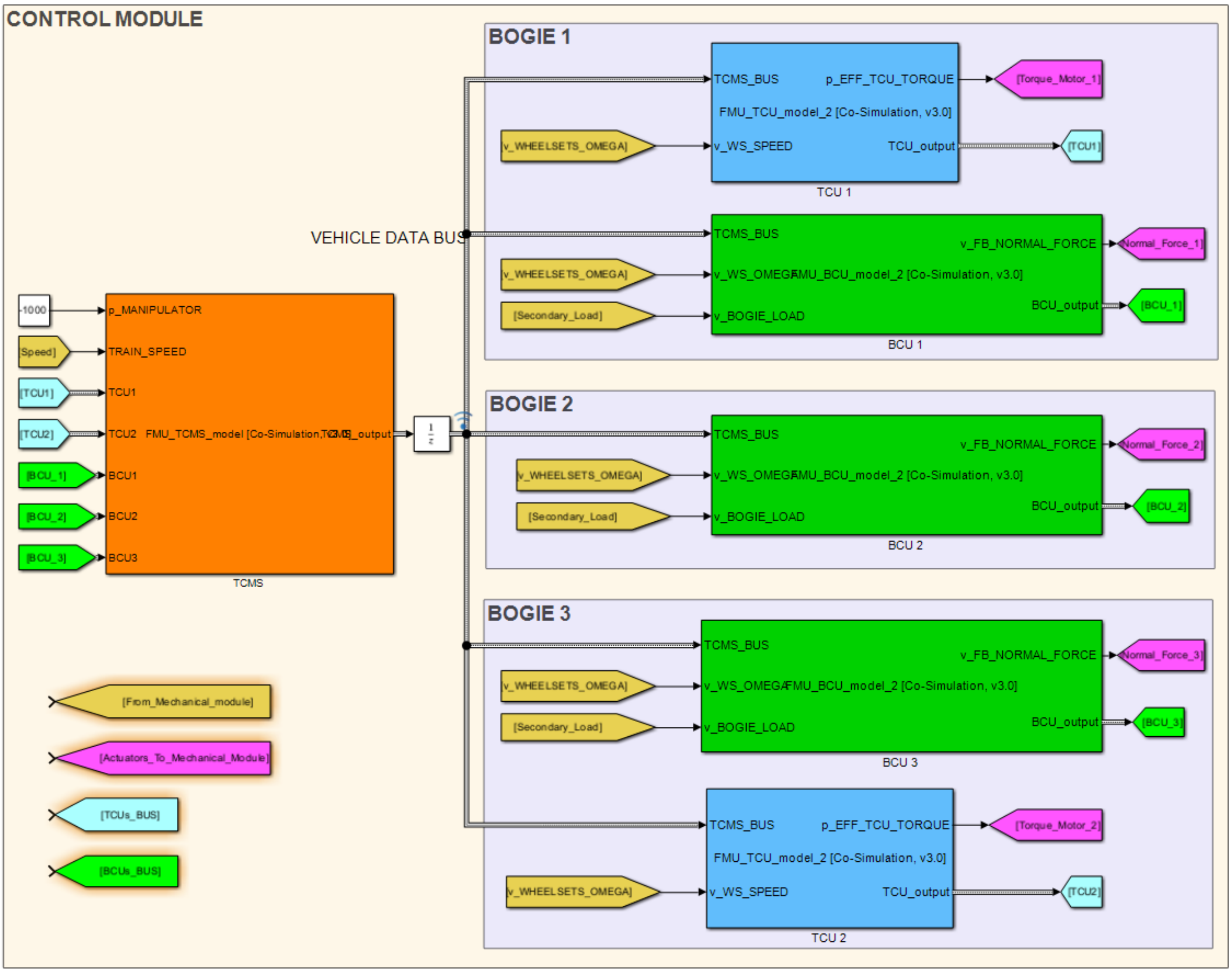

Figure 6. Control module based on FMUs

3.3 TCMS

TCMS (Train Control Management System) is the backbone of the train regarding its logic and electronics. To what concern B&T operation, it is responsible for managing the signals of different components into the vehicle data bus and performing functionalities such as speed estimation, setting effort commands, or defining operation mode, among others.

The TCMS receives the output from each TCU and BCU (as indicated in Tables 1 and 2) and updates the vehicle data bus, which is a unified data source from which any component reads all the necessary information to perform its operation. The vehicle data bus contains the variables listed in Table 3.

3.4 FMU-Based Control Model

The control model entirely based on FMUs is shown in Figure 6, which replicates the architecture of that shown in Figure 5. There are only three types of FMU: TCMS, TCU, and BCU types. The difference among TCUs and BCUs resides in the input parameters that identify their location in the vehicle. All TCUs and BCUs include a parameter to define the bogie that they belong to (p_BOGIE_INDEX). Moreover, the BCUs include another parameter to indicate that they belong to a motor bogie and the related TCU when it is defined as a non-zero value (p_TCU_INDEX). By using the latter, the BCUs can track the state of the TCUs and take the correct input data to perform blending from the vehicle data bus.

Figure 6 also includes a legend to indicate the type of signals. Yellow labeled tags are signals coming from the vehicle dynamics model: the speed, the wheelsets' angular velocities, and the load on the secondary suspension. By using the parameter p_BOGIE_INDEX, the TCUs and BCUs can select the correct values of the wheelsets' angular velocities and the load on the secondary suspension. The vehicle data bus is read by all the TCUs and BCUs from where they obtain the necessary information to set effort values (labeled in clear pink), which are subsequently sent to the vehicle dynamics model. Each TCU and BCU output a data bus that is sent to the TCMS that merges all the data to update the vehicle data bus accordingly. As mentioned before, the signals denoted as TCU_X, BCU_X and TCMS_BUS, are programmed as bus signals, that enable a flexible definition of variables. This makes possible to redefine interfaces avoiding changes in the control module.

4 Simulation and Verification

Vehicle dynamics and control models described in Sections 2 and 3, respectively, are coupled together. Figure 7 shows how the FMU of the vehicle dynamics model is coupled with the control module shown in Figure 6. The correct simulation of the model is checked by assessing its behaviour for different adhesion conditions, dry ($\mu_0 = 0.30$), wet ($\mu_0 = 0.10$), and contaminated surface ($\mu_0 = 0.05$) (Gallardo-Hernandez and Lewis 2008). Adhesion values, μ_0, are defined in the vehicle dynamics model as detailed in Section 2.

Figures 8 and 9 show the kinematic and effort results of the simulations, respectively. The simulation is a service braking operation from 80 km/h, which is about its maximum design speed to 0 km/h. In dry conditions, the braking distance is about 220 m. For wet conditions, the braking distance increases up to 260 m, which is 18% higher than for dry conditions. In this case, the vehicle is not able to sustain the maximum deceleration given by the dry

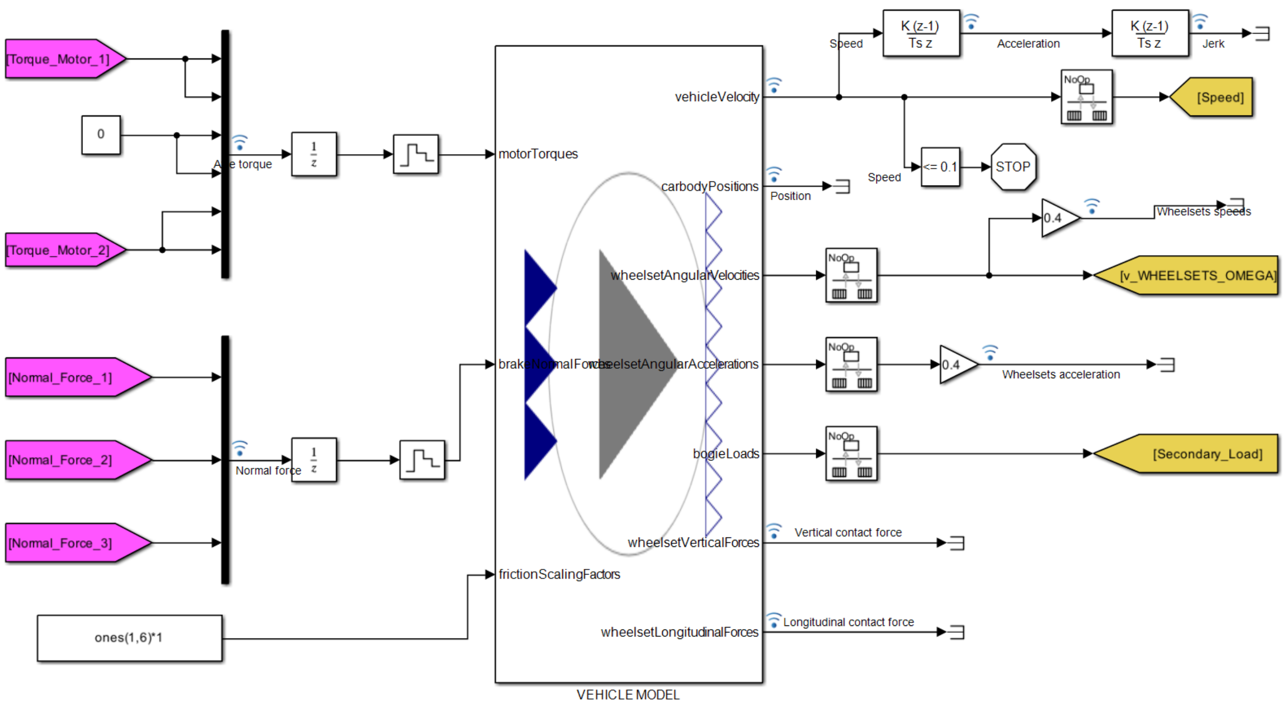

Figure 7. Vehicle module implemented along with the control module interfaces

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scenario, and it is reduced as a consequence of the WSP control. For very poor adhesion conditions, the braking distance increases up to 600 m. This value is significantly high and may not be acceptable in a real vehicle. Therefore, the definition of more aggressive braking modes as well as the modelling of rail cleaning phenomenon may be necessary to achieve acceptable braking distances in this scenario.

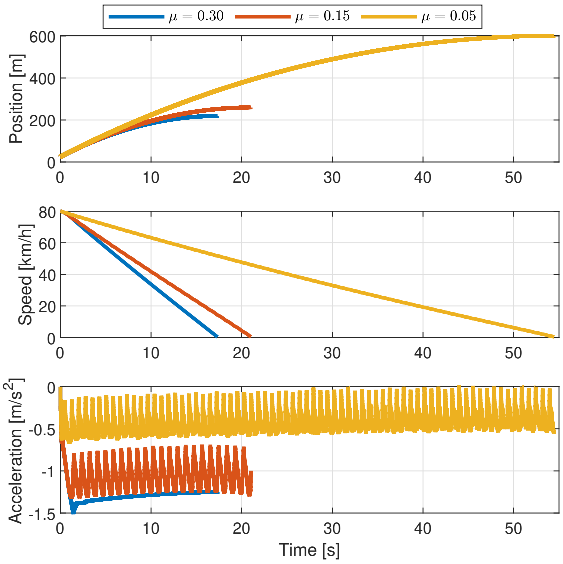

Figure 8. Vehicle kinematic results for different adhesion coefficients

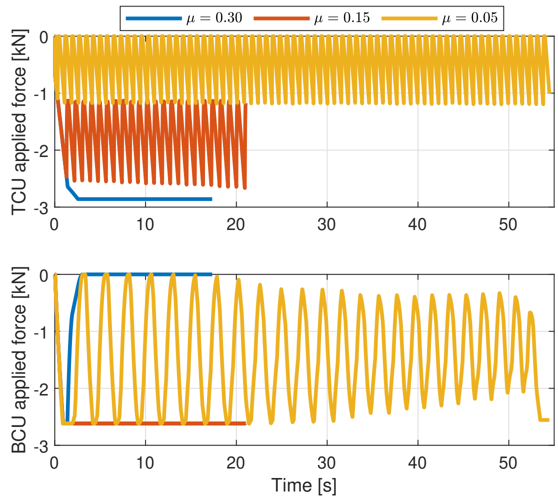

Figure 9. TCU and BCU applied efforts for the first and second bogie, respectively, at different adhesion conditions.

Regarding effort results shown in Figure 9, in the dry case, TCUs are able to provide all the braking deceleration except at the braking start. In the first seconds, the jerk-limitation prevents TCUs from increasing too quickly the effort and the BCU at the trailing bogie compensates for the braking effort deficit. Once the TCUs reach the requested effort, the BCU releases friction effort. For wet conditions, the TCUs start to limit the applied effort via WSP, while the BCU in the trailing bogie applies a constant effort to compensate for the braking deficit in the TCUs. For very poor adhesion conditions nor TCUs or BCUs are able to sustain the effort and both ED and pneumatic WSP start to limit the application of braking efforts. The ED effort is able to release and apply effort much faster than the pneumatic one.

The application of cyclic efforts due to the WSP is directly impacting on the wheelset speeds. Figure 10 shows the vehicle speed along with the linear speed of the wheelset, calculated as the angular velocity times the wheel radius, for the very poor adhesion conditions. As a consequence of the cyclic application of effort due to the WSP control under low adhesion conditions, the wheelset speed oscillates. When the effort is maximum the wheelset speed is minimum, while for close to zero efforts the wheelset speed approaches that of the vehicle. This shows how the WSP control is preventing the wheel from getting blocked, that would result in severe wheel damage.

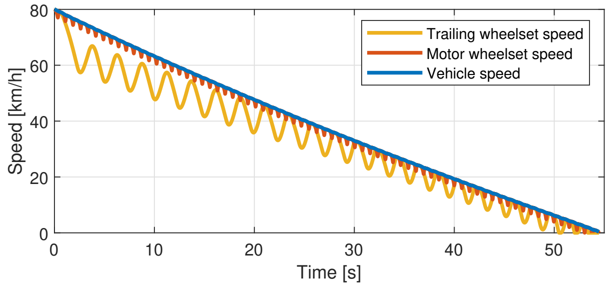

Figure 10. Wheelset speeds and vehicle speed comparison for the braking simulation with $\mu = 0.05$.

5 Digital Twin Context

Further to classical simulation applications as presented in section 4, the DT concept allows for comparison of the real world system with its digital model. Such evaluation can be used to enable improved operation as well as to monitor the current system integrity.

5.1 Improved Operation

In railway signaling, modern communications-based train protection systems like the European Train Control System (ETCS) (Wikipedia 2025) enable to run railway vehicles in *moving block* operation, where the minimum allowed distance between trains can be determined in real time. In this context, a B&T DT allows to estimate the current friction coefficient between wheels and rails (Schwarz 2021), which has significant influence on the possible braking distance (Marc Ehret 2024), and thus allows to determine optimal moving block lengths required between trains. In this way the utilisation of railway infrastructure can be increased, resulting in improved line capacity or safety.

5.2 Monitoring

Another possibility for taking advantage of a B&T DT is rolling stock monitoring. A contemporary approach is to compare sensor measurements of the real world vehicle with expected signals of the DT model using artificial intelligence methods. In this way it is possible to optimise maintenance intervals and to avoid damage and failure of railway vehicles. Hence, economic efficiency and reliability of railway transport can be improved.

6 Conclusions and Outlook

In this paper, collaborative DT development for railway braking and traction applications is presented. The developed DT clearly distinguishes two main domains, on the one hand, the vehicle dynamics involved in the braking and traction operation, and on the other hand, the elements performing the operation control. It is demonstrated that the basic concept of partners developing system modules with different tools as FMUs for DT applications can be applied successfully. Of course, this requires elaborate, iterative specification of interfaces and tuneable parameters.

Regarding the control domain, a modular structure of the control part recreating its real architecture is developed using FMUs basic units of the TCUs, BCUs, and TCMS. Communications among these components are represented via data buses that enable a versatile and compact definition of transferred data. These features are necessary to perform virtual validation and certification via substituting one or several basic units of the control module with the real unit under test.

The vehicle dynamics model successfully couples with the control module and provides it with any necessary physical signals to perform the control operation. Furthermore, this model has been proven to simulate low-adhesion conditions correctly. As a result, the B&T DT shows stable behaviour in degraded conditions such as low-adhesion scenarios. The control module activates WSP logic for both the ED and FB efforts, thus preventing wheel blockage during braking. This proves the feasibility of performing advanced virtual verification and validation of systems under extreme scenarios whose conditions are difficult to replicate via on-track tests.

In future work, the presented B&T DT is to be validated using real measurements that will give an insight of the accuracy level of the presented approach. Moreover, some other modules can be added as FMUs to increase the DT representativity, e.g., modules representing the track and ECTS/DAS/ATO.

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Disclaimer

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