Modularity as a Key Feature for Railway Digital Twins

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1. Introduction

As described in the Multi-Annual Work Program [1], Europe's Rail Joint Undertaking (EU Rail) aims at digitizing the railway sector and reach for concepts, models, technologies and methods associated to data, services and digital infrastructure. With this background, the concept of Digital Twins (DT) plays a prominent role in many if not in all EU Rail projects with numerous use cases ranging from virtual certification and automated train operation to the diagnosis and predictive maintenance of trains and infrastructure. Their development in EU Rail projects such as R2Dato or IAM4Rail is application-driven, i.e. specifically tailored to the respective application. This ensures high practical relevance and leads directly to results, but also carries the risk of incompatible ad-hoc solutions that are heavily dependent on individual applications and users or project participants, respectively.

Rather than treating DTs as monolithic solutions, the EU rail project FP1-MOTIONAL incorporates a cross-cutting task that considers them to be complex DT assemblies made up of modular, interoperable components. These components are regarded as valuable assets, and their secure, monetized exchange promises to be a compelling business model, which may unlock new efficiencies, reduce duplication of effort, accelerate innovation and supports scalability as well as cross-domain collaboration. This idea goes together with a parallel activity in FP1-MOTIONAL, which deals with the creation of a Federated Data Space for Rail based on the Gaia-X [2] principles. Besides the exchange of data, the concept of federated data spaces also addresses the option to exchange algorithms and analysis tools interpreted as DT components in this context which are presented as Apps in the reference architecture of the International Data Space Association (IDS) [3] as depicted in Figure 1-1.

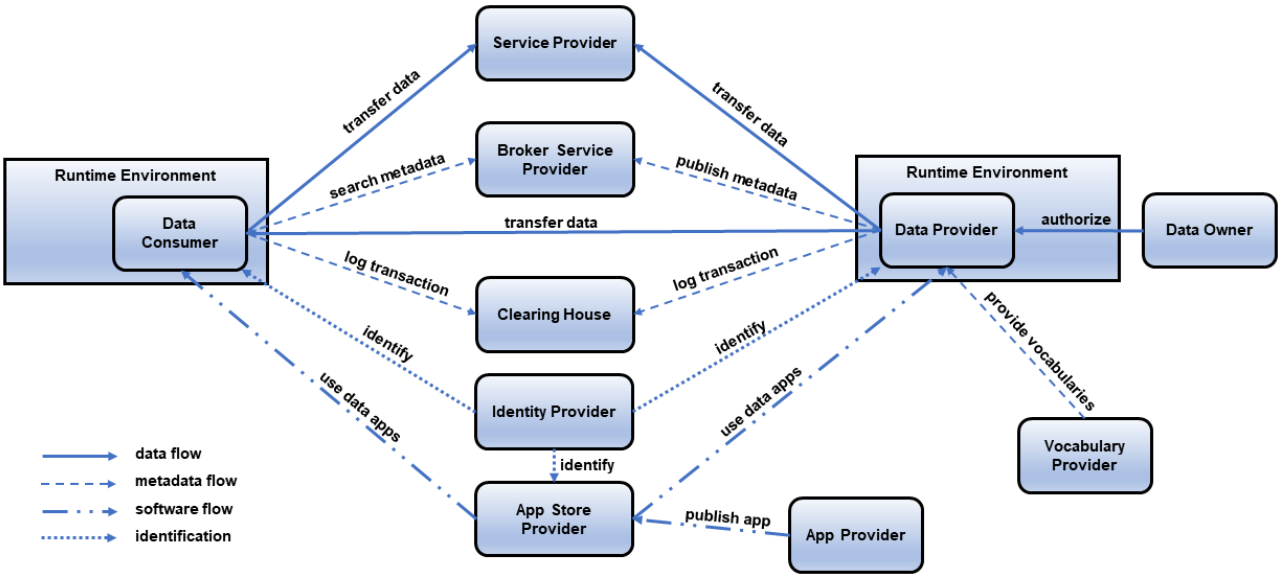


Figure 1-1: Reference Architecture of the International Data Spaces Association [3]

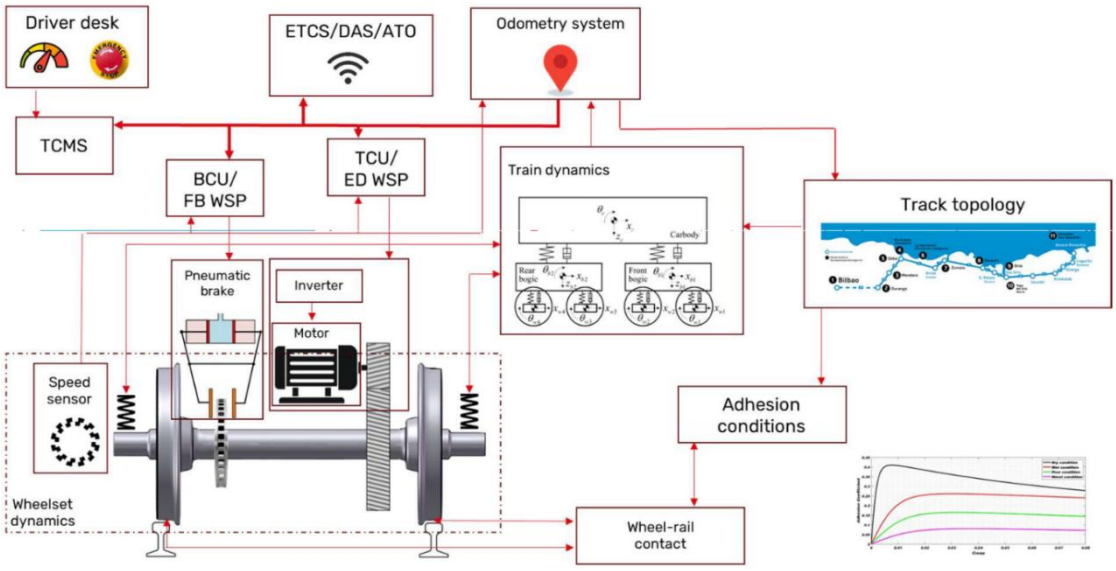


Figure 1-2: Architecture for a vehicle digital twin for braking & traction (Source: CAF)

Against this backdrop, the activities associated with FP1-MOTIONAL focus on decomposing complex systems into reusable components with standardised interfaces, cp. [4]. This is a conditio sine qua non for implementing the exchange of DT components as a business case. These activities and methods will now be presented using two different use cases.

2. Use Case Braking & Traction DT

The primary application of this example in Figure 1-2 is the virtual validation of control algorithms for braking and traction functions in rail vehicles. However, in contrast to the detailed technical description in [4], the focus here is primarily on explaining the ideas regarding modularity, interoperability and composability.

The initial decomposition of the architecture given in Figure 1-2 considers 3 main components, whereas the last one is additionally split up in three moduls:

- The description of the route along which the vehicle travels is based on waypoints that serve as interpolation points for a sufficiently smooth track curve specification, see [6] Section 3.1.
- The multi-body model of the vehicle dynamics includes wheel-rail contacts, vertical suspensions and two car bodies, see Figure 1-3. The braking and traction actuators here are as well incorporated in the vehicle model, but are candidates for further decomposition in future versions.
- The vehicle control system, see Figure 1-4, consists of the Train Control Management System (TCMS), several Traction Control (TCU) and Brake Control Units (BCU) that are taking the blending strategy, the motor characteristics and the available adhesion into account.

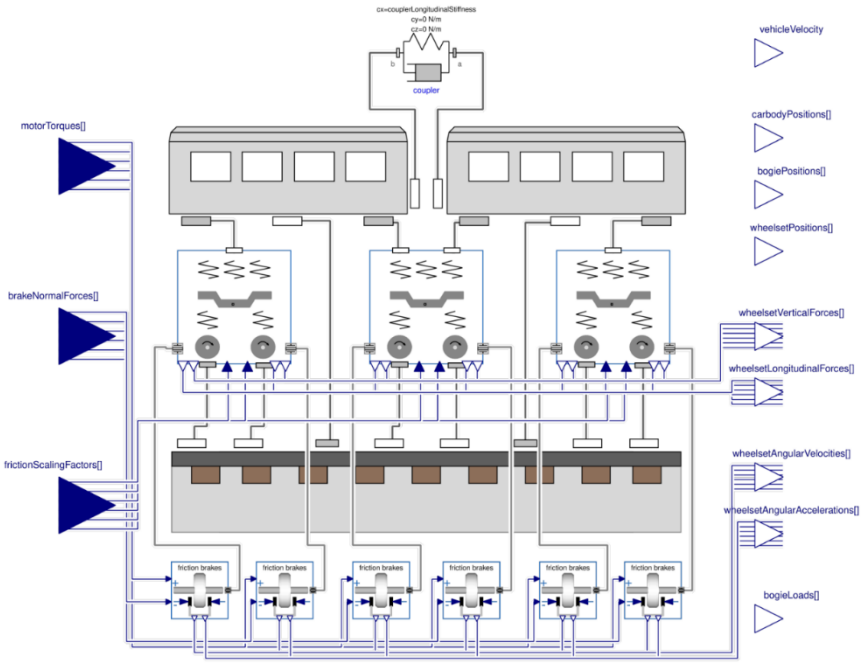


Figure 2-1: Modelica block diagram of the vehicle dynamics model

The vehicle model has been parameterized with 26 variables (mass properties, stiffness and damping values, and wind resistance coefficients) corresponding to the vehicle under consideration and in particular validated with regard to wheel-rail contact.

To verify the correct functioning of the overall system model thus formed, its behaviour was evaluated under wheel-rail friction conditions of dry (coefficient of friction μ_0= 0.30), wet (μ_0= 0.10) and soiled surfaces (μ_0= 0.05). The simulation scenario considered a service braking manoeuvre from 80 km/h, which corresponds approximately to the design speed, to a standstill. Figure 1-5 shows the resulting longitudinal kinematics of the vehicle. On a dry track, the braking distance is approximately 220 m.

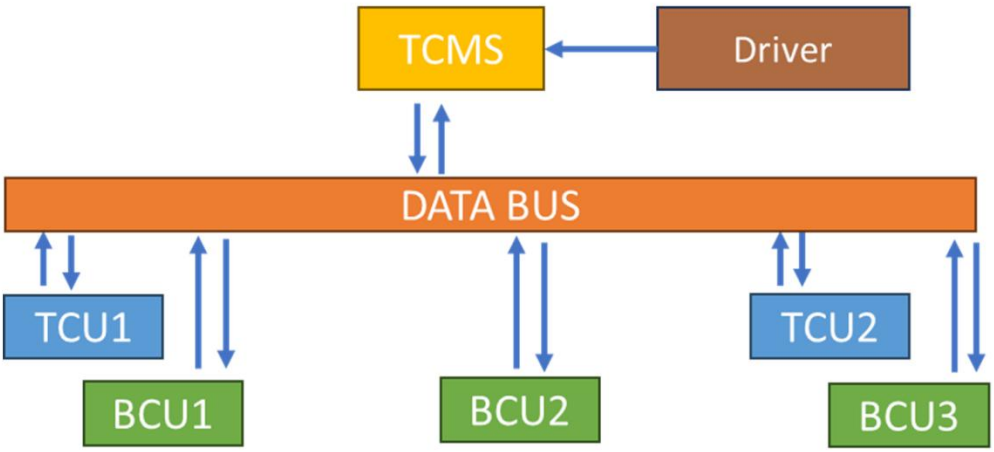


Figure 2-2: Control architecture of the vehicle

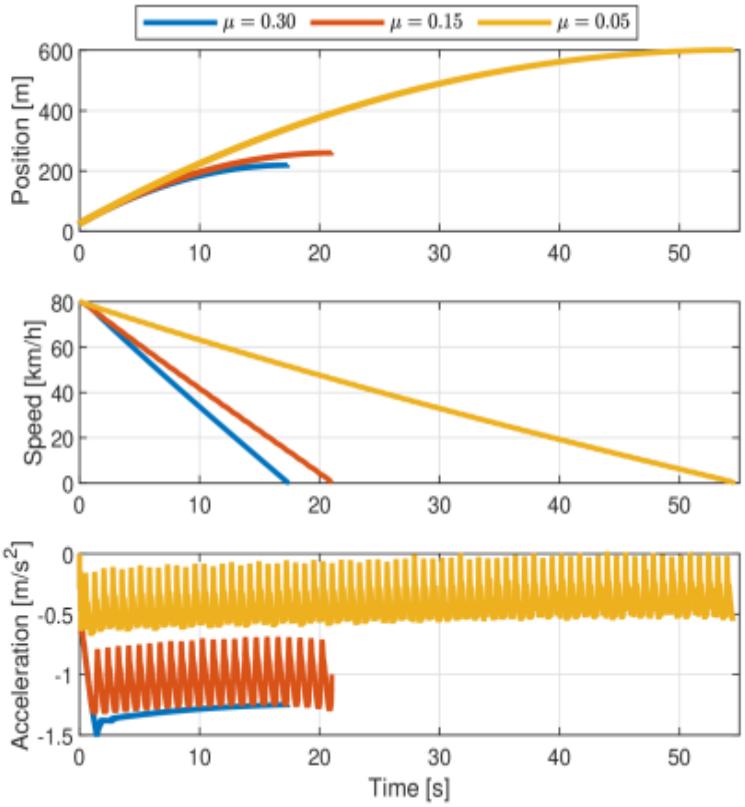


Figure 2-3: Braking disctances, speeds and accelerations for three different coefficients of friction

On a wet track, the braking distance increases by 18% to 260 m. In this case, the desired deceleration cannot be fully achieved and is therefore reduced by the anti-skid control system. In very poor adhesion conditions, the braking distance increases to up to 600 m. This value is very high, which is why measures to improve adhesion, such as sanding, would be recommended here, see [5] for a more comprehensive technical discussion.

3. Use Case Co-Simulation of Balise Error Identification

This use case depicted in Figure 1-6 is intended to compare two different information, one from the real world object, one from the virtual object:

- The real train runs along a given track, receives messages from the Eurobalises which are passed over and logs these messages or even transmits them as a real time data stream.
- The virtual train runs along the same track as the real train and passes over Balises, however uses the track design information in simulation in order to record virtual messages as they are to be expected by design.
- An algorithm compares these two records and issues an alert if a mismatch is observed, as it is visualized in Figure 1-7, where the two IDs 05053 ≠ 05052. This mismatch indicates a malfunction to the railway infrastructure manager, who then is in charge of introducing appropriate measures.

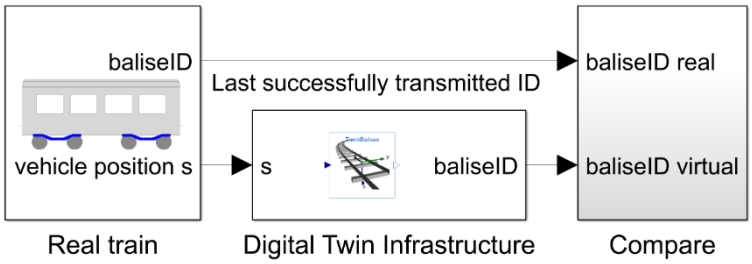


Figure 3-1: Balise Error Identification

Note, the messages nominated as real world messages above, are still results of a simulation, only. This limitation is due to the current status of the project. It will be brought closer and closer to the later application of the true DT as the Technology Readiness Level increases.

4. Modularity and interoperability aspects

4.1. The Functional Mock-up Interface

The Functional Mock-up Interface (FMI) [7] is an open, low-level standard for the exchange of dynamic simulation models, published and maintained by the Modelica Association [8]. It supports the creation of a virtual product as an assembly of component models and therefore corresponds exactly to the approach envisioned in Section 1. Initially released in 2010, more than 250 simulation tools, both open-source and commercial, in the meantime support the FMI standard.

This results in four key advantages:

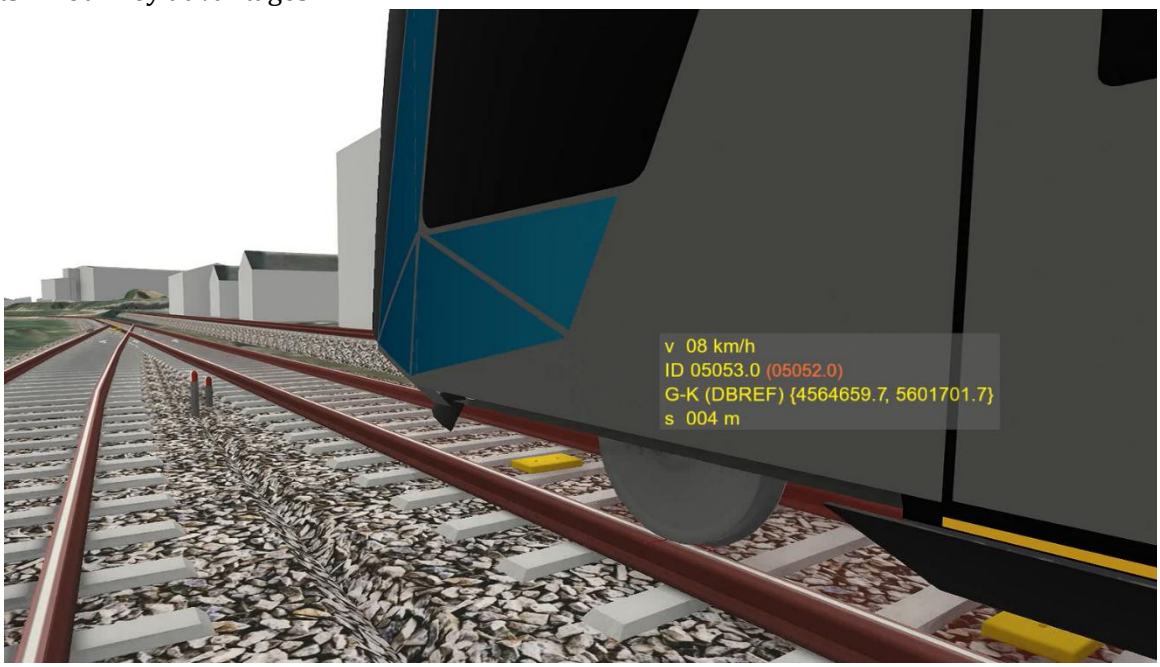


Figure 3-2: Visualization of a Balise ID mismatch.

1. Existing models do not need to be re-implemented for the modelling of DT components, but can simply be exported or imported as so-called Functional Mock-up Units (FMUs). So, the additional effort to make existing and validated models ready for exchange remains in a reasonable range.
2. Beside the export as open source model, FMI supports the export of binary files, so that intellectual property rights to the modelling content can be protected. Only the module's interfaces to its environment need to be disclosed and documented. This makes the suppliers involved more motivated to contribute their sub-models and support the interoperability and compatibility of the DT.
3. There is no requirement to use a specific runtime environment for executing simulation or analysis tasks. These tasks can be carried out on a local computer using a simulation program that supports FMU import. Further options include the *Distributed Co-Simulation Protocol* (DCP) [9], which organises the distributed co-simulation of FMUs, and the *Functional Interface for embedded Systems* (eFMI) [10] , which supports implementation and execution on a vehicle control unit, where technically feasible.
4. Building on FMI, the *System Structure & Parametrization* (SSP) [11] standard was developed. This allows the definition of model architectures as interconnected FMUs and organises their parameterization.

The vehicle modules from Sec. 2 and Sec. 3 and the Infrastructure Modul in Sec. 3 have been implemented in Modelica [8] using the Railway Dynamics Library [6] exported as FMU with open source code. The same applies to the Compare algorithm in Figure 1-6.

The control modules from Sec. 3 are initially implemented in Matlab™ and are exported as binary FMUs, since they contain competitive information e.g. on the wheel-slide protection algorithm.

As co-simulation environment for the Braking & Traction DT, Matlab™ on a local computer was used in order to generate the results in Figure 1-5. On a trial basis, the co-simulation scenario was also set-up in Modelica / Dymola and in a DCP-based tool called Multi-Agent Simulator [12].

So, a wide range of options including the SSP standard have been tested in FP1-MOTIONAL in order to validate the four advantages presented above.

4.2. The Infrastructure Description

To some extent, an exception as regards FMI exploitation is given for the track description in Sec. 2., which is specified by a file formatted in accordance to the ERA ontology [13]. As already noted, it contains the waypoints, required for the geometrical interpolation of the track curve. The multi-body simulation of the vehicle dynamics is closely coupled to the track geometry from the mathematical point of view which requires both ingredients, track geometry and multi-body model to be exported in one and only one FMU. Otherwise, a stable co-simulation cannot be organized. However, the track file is handled as an exchangeable file input to the exported FMUs, so that modularity could be enabled nevertheless.

Besides the geometrical track description, the track file also specifies infrastructure elements of control-command and signalling (CCS), power supply, structures such as tunnels, bridges and stations, as well as speed restrictions, etc.. This is exploited in the Co-Simulation of Balise Error Identification in Sec. 3, where the infrastructure file uses the same format and therefore exemplifies interoperability.

4.3. Interface Standardization

FMI offers a general specification to design interfaces from the implementation point of view, but does not comment on the physical information, on the specific in- and output signals to be exchanged between FMUs in co-simulation tasks. It is a matter of communication between suppliers and users, or EU Rail project participants, respectively in order to agree on the specific signals to be exchanged in co-simulation tasks.

As a first step to organize this communication FP1 MOTIONAL set-up a Gitlab repository which might be accessed throughout the EU Rail community. This repository is organized in two main folders:

- The so-called DT design time environment contains exemplary DT assemblies specified according to the SSP standard together with test data and documentation.
- The so-called DT support environment gathers FMUs as DT components. Their most relevant information is the interface, with which they are to be connected within an DT assembly. This is why the specific modelling content of the FMU is of minor importance and might be implemented in a very simple manner. In Figure 1-8 this is reflected by calling them minimal models.

In a specific DT use case application, it is assumed that these minimal model FMUs are replaced by more realistic proprietary FMUs which however is intended to use the same interface definition as the minimal model FMU. Project participants are free to provide these proprietary binary FMUs to the Gitlab repository on their own accord.

The possible relation of the repository to the business case vision in Figure 1-1 is depicted by the AP provider role in Figure 1-8 which might serve as a future gateway. In addition, Figure 1-8 also specifies the different options for the DT runtime environment as already noted in Sec. 4.1.

The further development of the repository will be a matter of discussion for the next wave of EU Rail projects. The aim is, of course, to extend, enrich and improve the contents of the repository, and to communicate with DT implementers throughout the different EU Rail projects. If all contributors agree, however, it is also an option to open up this repository to the public and facilitate the standardization of interfaces for complex DT assemblies within a larger community. A similar approach has been used in the automotive industry in the past, see [14].

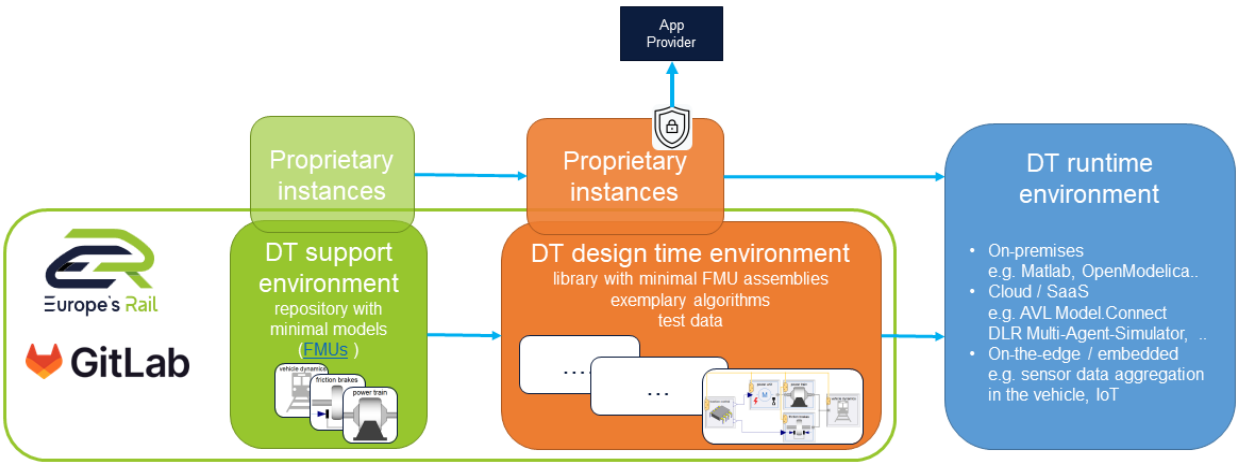


Figure 4-1: Repository for organizing modularity, interoperability and composability of Digital Twin components

5. Summary

This article presents ideas to facilitate the modular design of DTs and reports on associated activities within the FP1 MOTIONAL project. However, modularity is not presented as an end in itself, but rather as a means of enabling the exchange of DT components within a future business case in the Federated Dataspace for Rail, with the aim of making the railway sector more efficient, innovative and collaborative.

The ideas were illustrated using two examples, a DT for the virtual validation of control algorithms for the braking function and for the co-simulation for balise error identification. The advantages of exploiting the FMI standard and the ERA ontology for infrastructure description are presented.

Finally, the GitLab repository containing the initial version of the DT support and design time environment is introduced, which is intended as a facility to communicate and exchange on interface standardization within the EU Rail project community.

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