Aspects and Ideas for the FMI-based Modeling of Railway Digital Twins

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Abstract

This papers reports on activities in the European project MOTIONAL that aims at the development of a digital twin environment which facilitates the modularity, interoperability and composability of complex digital twin assemblies of railway systems. The approach that refers to the Functional Mock-up Interface is justified by a discussion of the comparable activities in industry and in the automotive field compared to particularities in the railway system. The work was initiated by the selection and analysis of nine use cases. An introductory digital twin example illustrates the current implementation status and related aspects, while an outlook presents the integration into the Federated Rail Data Space as the business case and as a vision of the activity.

Keywords: FMI, railways, digital twin

1 Background and Motivation

Europe's Rail Joint Undertaking (EU Rail) established by (Council of European Union, 2021) is the European public-private partnership for rail research and innovation. As described in (Europe's Rail Joint Undertaking, 2022), it aims at

- digitising and greening the railway sector,
- improving its efficiency, amenity, user-friendliness and maintainability,
- supporting the development of a globally competitive European railway industry and
- achieving the Single European Railway Area.

To this end, EU Rail organizes a series of projects[1]. MOTIONAL, the first in this series, inter alia addresses the topic of digitalisation of the railway sector and reach for concepts, models, technologies and methods associated to data, services and digital infrastructur.

The expected output shall be exploited by all EU Rail projects in accessing and exchanging data and in building and executing digital twins. The considered use cases range from virtual certification, automatic train operation to diagnostics and railway asset management originating from other EU Rail projects such as R2DATO[1] or IAM4RAIL[1].

With this background, the digital twin related work in MOTIONAL is specifically focussed on organizing a framework which facilities the **modularity**, **interoperability** and **composability of complex digital twin assemblies**.

After this section on the project background, a short literature review on digital twins and system simulations in railway engineering will be given. This is followed by a step-by-step derivation of the approach taken, which is then illustrated using an introductory digital twin model of specific signalling devices. A more elaborate digital twin model, which is associated to the system architecture in the right hand side of Fig. 1, is being presented separately in an acompanying paper entitled *Collaborative Digital Twin Development for Railway Braking and Traction Applications* at this conference.

2 Related Work

EU Rail mainly emphasizes the expected benefits such as improved safety, availability and lower operational costs in (Europe's Rail Joint Undertaking, 2022), but only roughly specifies the concept as **„ .. a Digital Twin is a virtual representation able to imitate the behaviour of a physical system during the spans of its lifecycle ..“**.

It is to the credit of (Sjarov et al., 2020) that they have narrowed down and contextualised the ambiguous, often misunderstood or misused term *digital twin* with the help of their very readable literature research. They conclude their overview on digital twin definitions by what they call "**the smallest common denominator, comprising a real and a virtual world being connected by streams of data and information**." (Singh et al., 2021) as well gives a good overview on characteristics and advantages of digital twins. (Van Der Valk et al., 2022) supplement their paper survey by a qualitative interview study with 15 industry experts. The interested reader may be referred to the long list of references of the three last-mentioned papers in order to find more specific digital twin literature,

The exploitation of the Functional Mock-up Interface (FMI) (Modelica Asssociation Project FMI, 2024) is a

[1]https://rail-research.europa.eu/eu-rail-projects

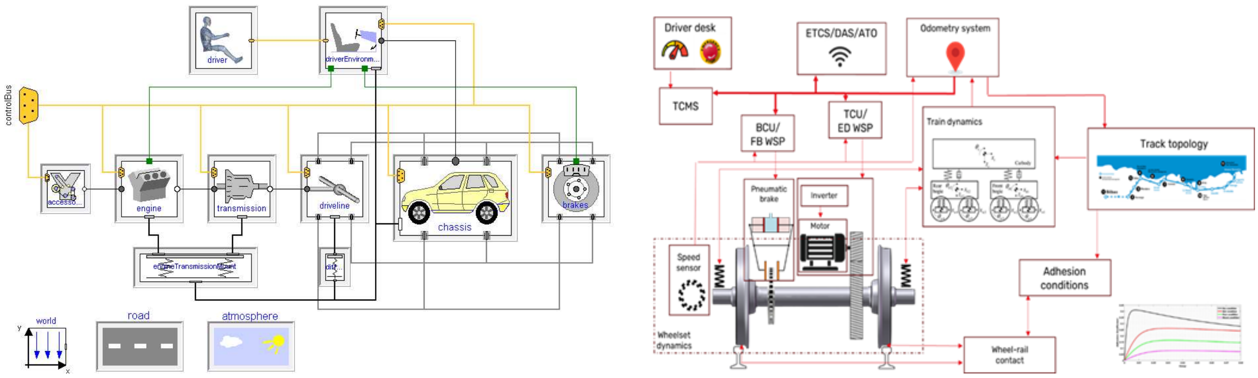

Figure 1. The system architecture of the Vehicle Interfaces Library (Dempsey et al., 2006) on the left compared to an initial architecture proposal in MOTIONAL on the right hand side (courtesy of CAF S.A.).

widespread strategy in order to build up digital twins by assembling individual component models. In fact, this free standard that defines a low-level interface to exchange dynamic models is well suited to organize the simulation of modular multi-domain systems pretty often required in digital twin applications, see e.g. (Wiens et al., 2021).

Although (Golightly et al., 2022) noted a low representation of scientific papers on FMI usage in railways, (Kugu et al., 2023) even used the System Structure and Parametrization standard (Modelica Asssociation Project SSP, 2024), which is layered upon FMI, to present two digital twin use cases from the railway domain. (Kugu et al., 2024) include the set-up and maintenance of digital twins into the Continuous Integration pipeline in order to control their changes and updates process.

The Modelica Railway Dynamics Library (Heckmann et al., 2019) provides the capability to consider vehicle dynamics issues such as traction, comfort and safety in multi-domain engineering tasks on different levels of detail. The library offers a convenient export of portable FMUs that may include railway vehicle particularities such as track joints or wheel-rail contacts. (Heckmann and Streit, 2012) explored the introduction of external infrastructure data given in the open XML-based format (RailML®, 2025) simulating the energy flow in electrical railway networks on which a fleet of railway vehicles is running.

3 Derivation of the Approach

3.1 Comparison to Automotive Activities

For the sake of exemplification of the objectives **modularity**, **interoperability** and **composability**, consider the modeling of a railway vehicle running along the track. This system maybe modularized in subsystems which e.g. represent the track infrastructure, the vehicle dynamics, the traction system, the brakes and so on. In the same manner as the real vehicle system is composed out of integrated subsystem hardware provided by supplying companies, the digital twin of the system is considered to be an assembly of subsystem models as well prepared by the same suppliers. Presumed that the interfaces of each subsystem modul, i.e. its input and output signals, are uniquely specified, the subsystem model of supplier A may be exchanged by the subsystem model of supplier B.

This concept corresponds to a coordinated activity in the automotive field which led to the initial release of the free Modelica Vehicle Interfaces Library (VIL) (Dempsey et al., 2006) in 2006. In fact, Fig. 1 demonstrates the comparability of the former automotive activity with the task considered in this paper by a face to face comparison of exemplary vehicle system architectures. As already indicated by the name, the focus of the VIL was the definition of standard interfaces, which allows for an easy exchange of submodels on brakes, engine, driveline and so on. The component models provided by the VIL only reflect their physical behavior on a very high, simplified level and are assumed to be detailed when actually used in practise. This is an important aspect which is intended to be considered in the context of the modeling of railway digital twins as well.

3.2 Particular Challenges

However, there are number of challenges which appear when the VIL approach is supposed to be transfered into the field of railway digital twins:

- It is a general observation that the modeling of railway vehicles is more complex than for automotive vehicles. It involves more mechanical degrees of freedom, since a train usually consists of more than one car and two-level suspensions are implemented to guarantee both separately, running stability and passenger comfort. In addition, a geometrical track description that is two-times continuously differentiable is required and the very stiff, geometrically and physically non-linear wheel-rail contact is a modeling and simulation challenge on its own, see (Heckmann et al., 2019).

- FMI is a free standard supported by more than 200 different commercial or open modeling tools.

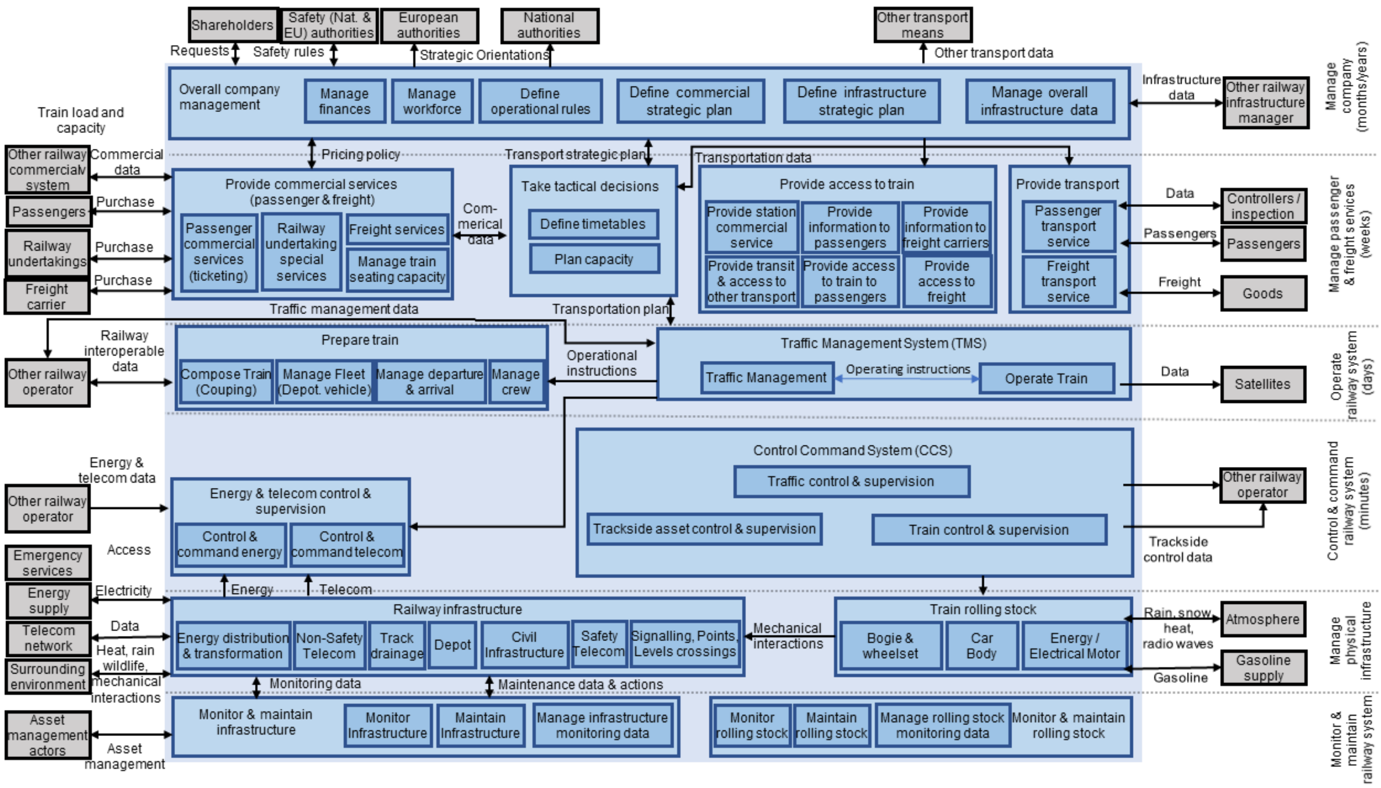

Figure 2. The high level railway system architecture as summarized by (LINX4RAIL, 2022).

Already existing models don't need to be re-implemented for digital twin modeling but simply can be exported as so-called Functional Mock-up Units (FMUs). Since FMI as well considers the export of binaries, the intellectual property on the modeling content also can be protected. The associated stakeholder is more motivated to contribute its sub-models and to support the **interoperability** and **composablity** of the digital twin. However as a disadvantage, FMI does not follow object oriented modeling concepts such as inheritance, which e.g. allows for the convenient extension of Modelica connectors or model interfaces of the automotive VIL. So the flexibility to implement different levels of modeling details reflected by associated interfaces is restricted.

- Fig. 2 presents an overview of the general railway system which has been generated in a predecessor project of MOTIONAL (LINX4RAIL, 2022). It is obvious that the railway vehicle architecture exemplified in Fig. 1 only covers a small area of the whole system. Functions such as traffic management, signaling, supervision, energy supply and so on are interrelated to the motion of the vehicle and increase the complexity. Therefore, it is assumed that not one and only but several interrelated modeling architectures are required to depict the whole railway system. This is why, use cases have been selected first in order to develop this architecture landscape step by step.

- There is another conceptual aspect of **modularisation** that appears in the light of Fig. 2: subsystem or component models should be distinguished from each other in such a way that each subsystem model can be provided by a single stakeholder, such as the infrastructure manager, the railway operator or the vehicle and equipment suppliers, etc. This way, the subsystem model reflects the expertise of the associated stakeholder, which in turn determines the content and conditions of the submodel provision.

- The digital twin concept is a very general one. Fig. 3, not at all meant to be exhaustive, illustrates aspects in which digital twins may differ in practise: they may address different phases of the product life cycle, cover specific components only or represent a complex model assembly, consider CAD geometry or take transient behavior into account, just reflect a stationary property or predict dynamic evolutions and so on. This high degree of individuality is a challenge for the endeavour to create a framework for complex digital twins in the railway field.

3.3 Interim Status

The objective of the digital twin activities in MOTIONAL is the development of a digital twin environment which facilities the modularity, interoperability and composability of complex digital twin assemblies originating from the railway system in Fig. 2. The work was initiated in 2023

Figure 3. Aspects in which digital twins may differ in practise according to (Stark et al., 2019)

by collecting and analyzing use cases, shortly summarized by the following list:

- Braking and traction of railway vehicles: Vehicle models such as in Fig. 1 and data from braking experiments are compared to verify and validate the brake system design.
- ERTMS[2] digital twin: On-board units of the train protection system are certified in hardware-in-the-loop laboratories.
- Pre-assessment of automatic train operation scenarios: The ERTMS digital twin environment above is extended for the sake of examination of future automatic train operations.
- Maintenance digital twin based on graph database: Data of past maintenance actions are analyzed in order to optimize maintenance scheduling and execution.
- Failure mode of point machines: The actuators of switches, so-called point machines are monitored for the purpose of optimizing their maintenance.
- Fault detection and diagnosis in the rail infrastructure: Multi-sensor data are fused and analysed in order to explore the AI-usage in infrastructure monitoring.
- Driver cabin HVAC[3] digital twin: HVAC sensor data and environmental conditions are analyzed to schedule maintenance.
- Station Asset Management Digital Twin: BIM[4] data of stations and IoT sensor data are fused.
- Bridge Asset Management Digital Twin: BIM and sensor data of bridges are used to monitor construction.

In parallel, a review of published activities in industry and in the automotive field together with EU Rail internal discussions provided additional ideas, arguments and aspects, which are reported in this section.

The ongoing implementation of the above use cases is stored in a GitLab repository hosted by the EU Rail and accessible by all EU Rail participants. In the long term, making the use case models accessible beyond the EU Rail network is desirable, but this still needs to be agreed by all contributors.

It turned out that the provision of and access to infrastructure data, including track topologies and geometries, signalling equipment, etc., is a prominent interrelation on which many use cases rely. This is therefore addressed in the introductory digital twin example presented in the following section.

As the above discussion and the cautious paper title suggest, the findings explained in this paper are merely the first stage of a longer journey. This point is reflected in the project description by demanding two validated digital twin uses case of Technology Readiness Level 5 (European Commission et al., 2017) for the project outcome until 2026, only. Further stages of this journey are covered in the Outlook section.

4 Introductory Digital Twin Example

4.1 ETCS Eurobalises

In Europe, many different and incompatible train protection systems are currently used by individual European Union (EU) member states. In order to improve interoperability, country-specific protection systems are to be replaced by the European Train Control System (ETCS). An essential part of ETCS are the so-called Eurobalises installed on the track, see Fig. 4 and (Winter, 2009).

An Eurobalise is a standardized electronic beacon system used to communicate vital information to trains. It may be understood as a smart rail road sign that "talks" directly to trains as they pass over it. These small, robust devices are mounted between the railway tracks and contain electronic circuits that transmit data to onboard train systems when a train's antenna passes above them. By default, the ID number and the geographic coordinates of the Balises are transmitted. Furthermore, they can tell a train important things like the maximum safe speed for the upcoming section of track, whether signals ahead are green or red, the distance to the next station, or warnings about track conditions.

[2]ERTMS: European Rail Traffic Management System
[3]HVAC: Heating, Ventilation, Air Conditioning
[4]BIM: Building Information Modeling

Figure 4. ETCS Eurobalise installed on the track see https://en.wikipedia.org/wiki/European_Train_Control_System, CC BY-SA 4.0

This system is crucial for modern train safety and automation, allowing trains to automatically adjust their speed or apply brakes if necessary, while also enabling features like precise positioning and automated train control across different European countries that previously had incompatible railway signaling systems. In the following, this introductory example tackles the monitoring of the Balise installations during daily operation.

4.2 Use Case Description

The use case 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. This mismatch indicates a malfunction to the railway infrastructure manager, who then is in charge of introducing appropriate measures.

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 digital twin as the Technology Readiness Level increases in the course of the project.

4.3 Modeling of the railway infrastructure

When working with digital twins that represent parts of the railway system, the appropriate modeling of the infrastructure is an essential component. However, the modeling requirements differ considerably depending on the specific use case. An incomplete collection of these is listed below:

- For vehicle dynamics simulations, detailed knowledge of both track layout and irregularities is mandatory
- Breaking and traction scenarios require data such as the current track gradient, speed limits and friction conditions between wheel and rail
- Railway dispatchers are dependent on an enhanced description of the railway network. This includes signalling facilities such as Eurobalises already mentioned in Section 4.1

The applications just presented make it clear that many different requirements are imposed on the description of railway infrastructure. Therefore, it is difficult provide one model which covers all scenarios simultaneously. Even if it were possible, the model would be overloaded with extensive data making it unnecessarily complex.

Therefore, it is proposed to provide a basic track model, as already exists in the Railway Dynamics Library (Heckmann et al., 2019). It only provides a rudimentary description of the track layout. The 3D-curve of the track contained in this model consists of B-Splines which are defined by supporting points imported from a track file.

If further demands are put on the description of the infrastructure, a more comprehensive model can be derived from the basic track model through inheritance. An example of this approach is shown in List. 1. The code snippet outlines the *TrackBalises*-model. Note that the corresponding graphical representation is shown in Fig. 5. It extends the features of the basic track model by outputting the ID number of the last crossed Balise based on the current vehicle position.

Listing 1. Track model extended with data on installed Eurobalises along the track

```
within RailwayDynamics.General;
model TrackBalises
  extends Track;
  import Modelica.Blocks.Tables;
  import Modelica.Blocks.Types;
  import Modelica.Blocks.Interfaces;

  Tables.CombiTable1Ds lookupTable(
    fileName="balises.mat",
    smoothness=Types.Smoothness.
       ConstantSegments);
  Interfaces.RealOutput baliseID
    "ID of the last crossed balise";
  Interfaces.RealInput s
    "Vehicle position along track";
equation
  connect(baliseID, lookupTable.y);
  connect(s, lookupTable.u);
end TrackBalises;
```

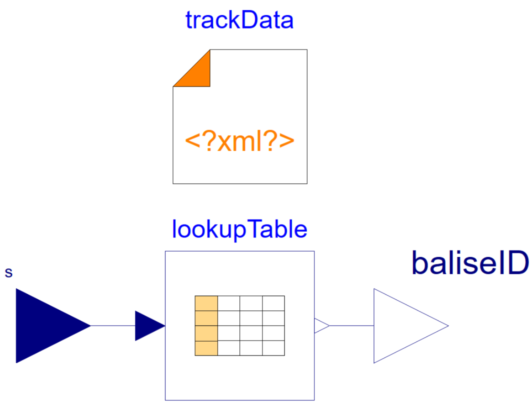

Figure 5. Graphical representation of the *TrackBalises*-model

4.4 Track description

In Section 4.3 a basic track model was introduced that provides a fundamental infrastructure description via supporting points imported from a file. In this paper we focus on a XML-based track description. In practice, however, there are many country-specific formats. It is therefore planned to support a more general approach for future work using ontologies, see (Camarazo et al., 2025).

In the XML-based data format the railway network is described as a graph in which nodes are connected by links. In the following, links are to be considered as track sections. A generic representation of a railway network is presented in Fig. 6.

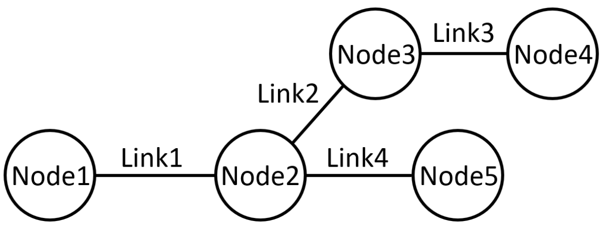

Figure 6. Graph of a generic railway network, which consists of nodes and links

The corresponding textual description of the railway network is shown in List. 2. It contains a 'Link'-element representing a track section, which is identified by the tag 'GlobalId'. Its start and end points are defined by 'FromNodeId' and 'ToNodeId', respectively, which are in turn identifiers of the corresponding 'Node'-elements. Other data included are section length and geographic coordinates of the supporting points which are used for interpolation as already mentioned in Section 4.3.

In addition to the pure track description, the track file contains data on Eurobalises installed on the track. Note that they are referred to in the file with the generalised term 'InformationPoint'. In our case, only data about the ID of the Balise and the distance travelled from the start point of the track section to the Balise are relevant.

The import of supporting points describing the track layout as well as corresponding Balise data is carried out using the ExternData library (Beutlich and Winkler, 2021). The imported data is stored in different arrays for further processing.

```xml
<?xml version="1.0" encoding="utf-8"?>
<BaseRoot>
  <Infrastructure>
    <Links>
      <Link>
        <Identification>
          <GlobalId>Link1</GlobalId>
          <FromNodeId>Node1</FromNodeId>
          <ToNodeId>Node2</ToNodeId>
        </Identification>
        <Length>TrackLength</Length>
        <Coordinates>
          <Coordinate>Coordinates1</Coordinate>
          <Coordinate>Coordinates2</Coordinate>
          <Coordinate>Coordinates3</Coordinate>
        </Coordinates>
      </Link>
    </Links>
    <Nodes>
      <Node>
        <GlobalId>Node1</GlobalId>
        <Coordinate>Coordinates4</Coordinate>
      </Node>
      <Node>
        <GlobalId>Node2</GlobalId>
        <Coordinate>Coordinates5</Coordinate>
      </Node>
    </Nodes>
  </Infrastructure>
  <InformationPoints>
    <InformationPoint>
      <Identification>
        <GlobalId>Point1</GlobalId>
        <FromNodeId>Node1</FromNodeId>
        <ToNodeId>Node2</ToNodeId>
      </Identification>
      <DistanceFromNode>Dist</DistanceFromNode>
      <Coordinate>Coordinates6</Coordinate>
      <BaliseGroup>
        <Balise>
          <GlobalId>BaliseID</GlobalId>
          <Data>BaliseData</Data>
        </Balise>
      </BaliseGroup>
    </InformationPoint>
  </InformationPoints>
</BaseRoot>
```

Listing 2. Textual description of a generic railway network

4.5 Simulation environment and FMU export

The use case outlined in Section 4.2 shall be supported by the usage of digital twins. The system presented in Fig. 7 is used for this purpose. Note that the simulation environment was created with Simulink (The MathWorks Inc., 2024), however, the individual components are based on the Modelica language and are exported as FMUs for further usage. This was done to emphasise the interoperability of the models used.

The system consists of the following components:

- The signals that come from a *real train* are summarised in one component. While running along a

 DOI 10.3384/ecp21891

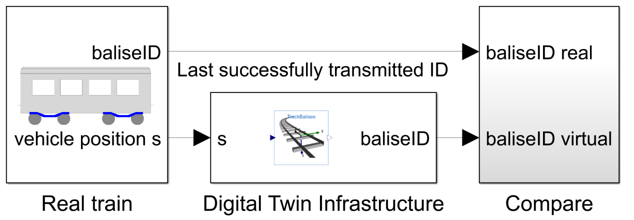

Figure 7. Illustration of the Digital Twin environment for the present use case

given track, the last successfully Balise ID number transmitted to onboard train systems is output. Furthermore, the current train position s is issued to the simulation environment. As already mentioned in Section 4.2, the messages nominated as real world messages, are still results of a simulation, only.

- The *TrackBalises*-model introduced in Section 4.3 takes on the role of the *digital twin of the infrastructure*. It takes the real train position signal as input and, based on imported track data as described in Section 4.4, outputs the ID number of the last crossed Balise. After exporting this model as FMU, a string parameter provides the path to a file from which track data is imported. Furthermore, since the XML-file format describes a whole railway network and not just one track, another string parameter has to be provided which represents the identifier of a specific track section. Besides XML-based description, it is currently possible to read track data in *.trm file format as used in Simpack (Dassault Systèmes, 2024).

- The task of the third component is to *compare* the signal from the real train with that of the digital twin. A graphical representation of the preliminary underlying model is presented in Fig. 8. The ID numbers of all Balises are integers. As soon as the difference between the two signals is greater than or equal to 1, it is assumed that the ID numbers do not match.

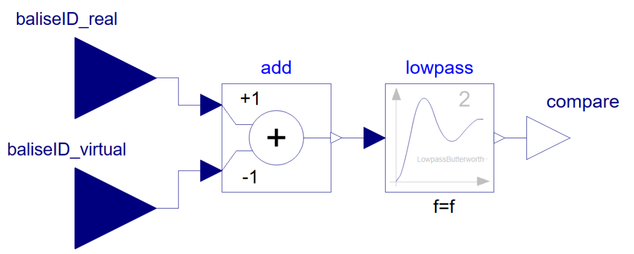

Figure 8. Graphical illustration of the *Compare*-model

The Balise ID numbers as signal outputs of both real train and digital twin come from different sources, but should be identical. As soon as a deviation occurs, this might indicate that a Balise did not transmit any data.

Note that the signals being processed in the *Compare*-model require low pass filtering. This is necessary in order to filter out high-frequency signals that might occur if the train onboard systems and FMUs shown in Fig. 7 use different sampling rates. Furthermore, it is worth to mention that the *Compare*-model presented in Fig. 8 should be considered as initial proposal. Other possible error sources such as inaccurate positioning data or time delays are not taken into account yet.

4.6 Results

An exemplary output generated in the context of the Eurobalise use case is presented in Fig. 9. The current position of the real train is shown in the top plot. The subplots in the centre show the ID number of the last crossed Balise issued by the train onboard system and the digital twin, respectively. Both signals are kept constant until the next Balise is crossed. The bottom plot shows the output of the *Compare*-model. It is clearly visible that there is a mismatch of the recorded Balise ID numbers at track position 5500 m. This indicates that a Balise did not transmit data to the train correctly and therefore should be revised.

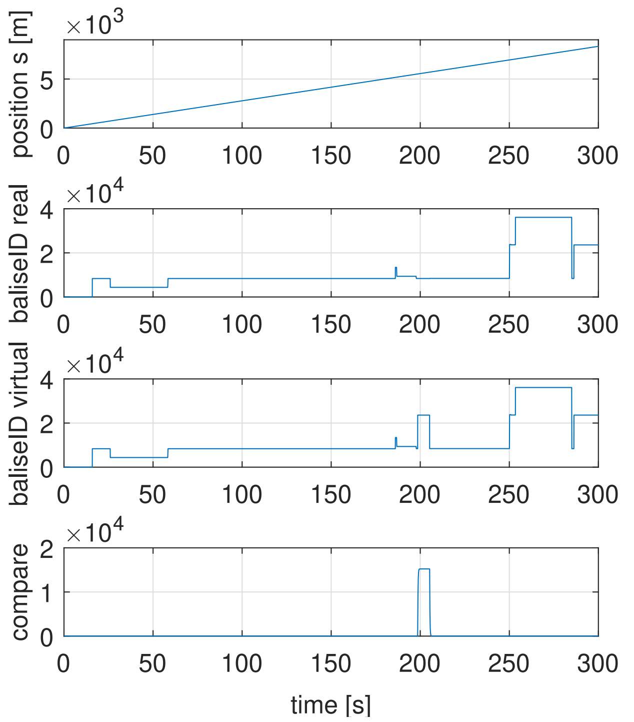

Figure 9. Exemplary history data that shows which Balise was last crossed

To make the comparison presented in Fig. 9 possible, the vehicle position along a specific track section of the digital twin and the actual train must coincide. For this purpose, the first successful transmission between Eurobalise and vehicle can be used for initialization.

The current work is dedicated to the elaboration of the use cases described in Sec. 3.3. Assuming that work can be continued in the next EU Rail funding period, a further improvement in the Technology Readiness Level and the number of validated use cases will certainly be sought.

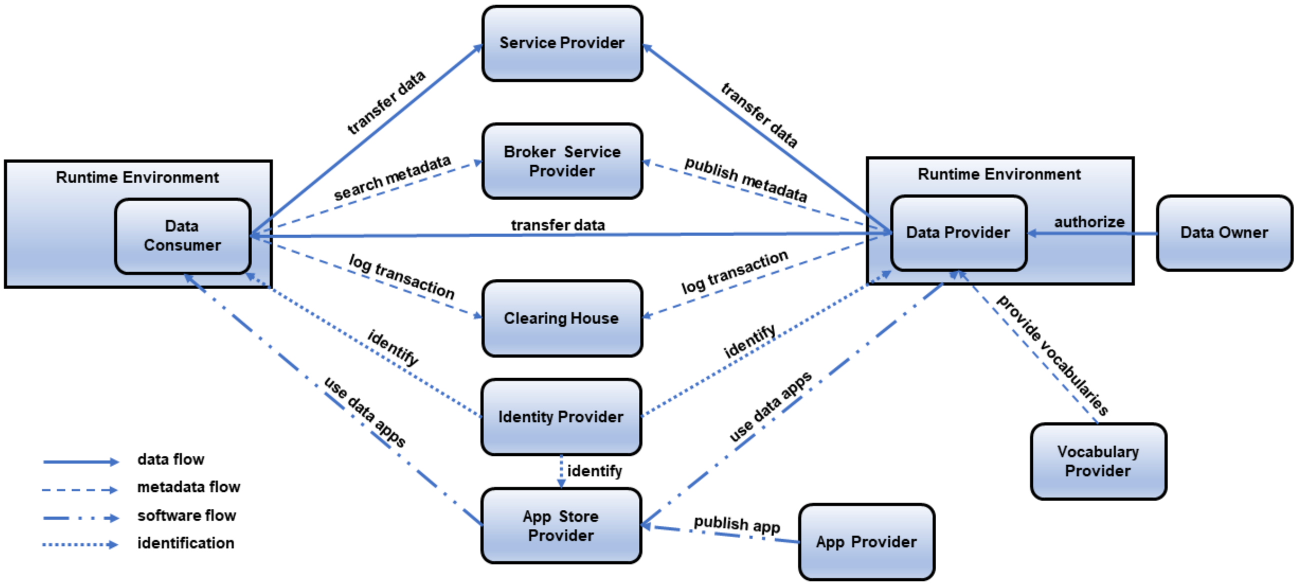

Figure 10. Reference Architecture of the IDS, cp. (Bader et al., 2020)

5 Outlook

As mentioned in Sec. 1, digital data, services and infrastructure are high level objectives of EU Rail. This is why, a parallel activity in MOTIONAL deals with the creation of a Federated Data Space for Rail. Data Spaces based on the Gaia-X[5] principles such as interoperability of data and services, sovereignty over data, security and trust use a concept of data integration without a central data repository. Data remains at its original source and is only exchanged peer-to-peer, if the transfer is explicitly requested and authorised. A data space, formed by the totality of its participants, is a distributed, federated structure with many data providers, consumers and services. The following enumerates, literally quoted from (Kraemer et al., 2023), the expected benefits related to Gaia-X business models:

- Efficiency: data is only exchanged when and to the extent necessary.
- Security: Data is protected from unwanted access.
- Control: Participants can determine exactly what access others have to their data.
- Transparency: Participants are given the necessary knowledge to decide for or against an exchange.
- Quality: Data and services are insured to be of the specified quality.
- Scalability: Required resources can be accessed as needed, quickly and comprehensively.
- Regulatory compliance: The Gaia-X ecosystem is in line with the values and laws of the European Union.

The concept has its main origin in the work of the International Data Space initiative (IDS)[6] (Bader et al., 2020). Fig. 10 presents the reference architecture of the IDS, which also considers the exchange of software tools and algorithms, addressed as applications or apps in Fig. 10.

In our context, the role of a digital twin developer corresponds to the role of an *App Provider* in terms of the IDS. Future digital twin activities in EU Rail will deal with the realization of this concept, which may be interpreted as a future business case for digital twins.

Acknowledgements

The authors gratefully acknowledge the financial support from Europe's Rail Flagship Project 1, MOTIONAL, grant agreement ID 101101973, HORIZON-ER-JU-2022-01.

Disclaimer

Although funded by the EU, views and opinions expressed are however those of the authors only and do not necessarily reflect those of the EU or EU Rail. Neither the EU nor the granting authority can be held responsible for them.

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