Transportation Engineering 15 (2024) 100222

Contents lists available at ScienceDirect

Transportation Engineering

journal homepage: www.sciencedirect.com/journal/transportation-engineering

A communication platform demonstrator for new generation railway traffic management systems: Testing and validation

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ARTICLE INFO

Keywords:
Railway traffic management systems
Integration layer
Common data model
Technological demonstrator
Integration of networks and services

ABSTRACT

Current rail traffic management and control systems cannot be easily upgraded to the new needs and challenges of modern railway systems because they do not offer interoperable data structures and standardized communication interfaces. To meet this need, the Horizon 2020 Shift2Rail OPTIMA project has developed a communication platform for testing and validating the new generation of traffic management systems (TMS), whose main innovative features are the interoperability of the data structures used, standardization of communications, continuous access to real-time and persistent data from heterogeneous data sources, modularity of components and scalability of the platform. This paper presents the main components, their functions and characteristics, then describes the testing and validation of the platform, even when federated with other innovative TMS modules developed in separate projects. The successful validation of the system has confirmed the achievement of the objectives set and allowed a new set of objectives to be defined for the reference platform for the railway TMS/Traffic Control systems.

1. Introduction

The railway sector is undergoing a process of progressive digitalization that can push forward the evolution of the railway transport mode as passenger and freight mass transport mode. This transformation is also driven by the growing focus on societal needs and environmental sustainability. The introduction of Information and Communications Technologies (ICT), whose applications is already consolidated in other domains such as automotive or industrial applications, can make this transition more effective, managing the complexity of the railway systems, overcoming their limitations and making them more efficient and attractive for their end users (passengers, freight transportation operators, etc.) [1,2].

Railways Traffic Management Systems (TMS) are used by the Infrastructure Managers (IMs) in the Operations Control Centers to manage the railway systems allowing the complete view and management of all the components involved in the traffic, from the monitoring of the trains movement to their automatic routes setting, with the aim of increasing the network capacity without jeopardizing the safety of passengers and trains. This involves accessing of data from various subsystems, i.e., the internal Rail Business Services (RBS), such as Interlocking, Radio Block Center (RBC), Energy Grid Management, Maintenance Service, and the external services, such as Passenger Information System (PIS) and Weather Forecast. Furthermore, the data from different TMS are involved. However, the development and evolution of the railway TMS were based on proprietary architectures (on the national basis but also depending on the different operators within a nation) that hindered their interoperability due to the lack of standardized interfaces and interoperable data structures. This negatively impacts on the systems updating and requires multiple development of applications for different systems.

In this context, the design of new generation railway TMS based on standardized communications interfaces and data structures eases and supports the cooperation between TMSs through the integration and use of different types of data also from different sources. Indeed, the development of the communication protocols and infrastructure, suitable to support a seamless exchange of data, facilitating TMS

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https://doi.org/10.1016/j.treng.2023.100222
Received 23 May 2023; Received in revised form 10 October 2023; Accepted 3 December 2023
Available online 10 December 2023

interoperability, is a key milestone on the roadmap towards implementation of future TMSs, that can also be enabled by the development of a testing environment where TMS applications can be tested before the field tests. Furthermore, this approach represents a step forward towards the multimodality, scalability, and sustainability of new TMS.

This paper presents the outcomes of the H2020 Shift2Rail OPTIMA[1] project [3] deepening the description provided in [4] with a particular focus on the final validation activities and results, completed in April 2023.

The main goal of OPTIMA is to address the aims of the Shift2Rail (S2R) Joint Undertaking[2] that promotes the development and the implementation of new technologies for railway TMSs. In particular, OPTIMA is closely linked to S2R Technology Demonstrator 2.9 (TD2.9) that aims "to specify and design a new TMS based on standardised frameworks, data structures, real time data management, messaging, and communication infrastructure including interfaces for internal and external communication between different subsystems, applications and clients. It aims for significantly higher integration of status information of the wayside infrastructure, trains, and maintenance services together with management of energy and other resources" [5].

OPTIMA designed, implemented and validated a Communication Platform Demonstrator (CPD) for the testing and validation of new industry solutions for new generation TMSs, as described by Cecchetti et al. [6]. This makes possible the testing of the systems and applications before the testing phase on the field that is more difficult from the organization point of view and risky. The key point of the architecture of the OPTIMA CPD is its compliance with the requirements defined by the related S2R projects In2Rail [7] and X2Rail-2 [8]. Therefore, the CPD was designed as an open platform that works as a middleware allowing the seamless and standardized communications between the involved systems and services. OPTIMA CPD provides a standardized communication system by means of an Integration Layer (IL), which uses standardised and interoperable data structures and processes based on the definition of a Common Data Model (CDM) for the data exchange between different RBS and external services.

The testing and validation activities are described, explaining the criteria adopted for the design of the test programme and the planning of the tests internal to the OPTIMA project to assess its performance and characteristics using specific Key Perfomances Indicators (KPIs) derived from the requirements of the systems and of the OPTIMA complementary projects X2Rail-4 [9] and FINE-2 [10]. The test scenarios used to generate the test data are also considered. This allowed the assessment of the OPTIMA Communication Platform Demonstrator and the TMS and services connected to the platform when it is set up as a testing environment. Furthermore, in addition to the internal tests, the testing of the CPD compatibility with modules developed by industry and agreed in close collaboration with the complementary project X2Rail-4 are extensively illustrated. An IL gateway was developed within the OPTIMA project to allow the federation of the OPTIMA IL with the IL of X2Rail-4 demonstrator to build a large-scale demonstrator called "TMS Cloud". It allows X2Rail-4 prototypes to connect to the OPTIMA IL and successfully access the OPTIMA CPD resources.

The paper is structured as follows. In Section 2 the architecture of the OPTIMA Communication Platform Demonstrator is illustrated in detail, focusing on its components. Section 3 describes the testing and validation activities of the CPD, illustrating the test program, some examples of internal test and the external testing activities. Finally, in Section 4 the conclusions are drawn along with a brief description of the future perspectives.

[1] OPTIMA is the acronym of "cOmmunication Platform for TraffIc ManAgement demonstrator".

[2] https://shift2rail.org

2. Communication Platform Demonstrator architecture

The architecture of the OPTIMA Communication Platform Demonstrator rests on four fundamental pillars: a) the interoperability middleware composed by the Common Data Model and the Integration Layer with its services, b) the data provided from the railway field, i.e. from the Rail Business Services and the external information services, c) the Application Framework (AF) where the Traffic Control (TC) and TM (Traffic Management) applications are running, d) the Operator Workstations (OW) used to interact and operate with the demonstrator as usually performed in the Traffic Control rooms (see Fig. 1).

All these components are conceived to cooperate with the aims to answer to the current needs of railways stakeholders and users. As explained in Section 1, current TMS lacks of seamless data exchange that impact on the diffusion of the railway transport mode as passengers and freight mass transport mode. Indeed, the different format for the data that the TMS applications of diverse stakeholders need to share jeopardize the interoperability of the overall railways system jeopardizing the efficient management of the railways network where different stakeholder operate, such as at the national boundaries. Furthermore, the absence of standard interface models affects the efficient update of the systems and impact, again, on their interoperability. As a results, the efficient management of the network capacity is hard to reach as well as its fast update to the more recent technologies. Finally, railways operators and infrastructure managers need the availability of tools for the testing of novel TC-TM modules before the field test that implies some criticalities.

2.1. The Common Data Model

The proposed demonstrator is based on a "data model" which provides semantics and a structure for the information exchanged. This model is the result of an intense research activity within S2R carried out by several projects (the three most recent are X2Rail-2, X2Rail-4, LinX4Rail), which have produced successive versions of these models and assorted linked open vocabularies [11]. General orientation is to provide open, modular, and extensible models under the generic name "Common Data Model" (CDM) that are not limited to the use cases originally intended by their authors. These efforts are now pursued under the MOTIONAL [12] project.

In particular, the goal of the LinX4Rail [13] project was to "develop and promote a common functional railway system architecture for the railway sector, as requested by the European Commission. Therefore, the purpose of a CDM widely adopted by the railway sector is to set the standard for interactions between legacy and new systems, thus ensuring sustainable interoperability between systems". Moreover, the data model developed inside OPTIMA federates most of the outcomes of EULYNX DataPrep [14], Railway System Model (RSM) [15], X2RAIL-4, Transmodel [16] and IFC Rail [17]. In this context, OPTIMA can be seen as a testbed for some concepts behind the CDM, as explained in [18].

Furthermore, OPTIMA has fully adopted the Platform Specific Model (PSM) produced by X2Rail-4, by virtue of offering two serialization formats that can be used interchangeably via Application Program Interfaces (APIs): a human readable format (JSON) and a binary format (Protobuf). The X2RAIL-4 model has been expanded according to the OPTIMA requirements and the new systems present only in its scope. In order to maintain compatibility with the pre-existing schema, this extension was implemented using the following two approaches: a) by using UML and then manually transposing the model into the X2RAIL-4 JSON schema that defines the X2RAIL-4 model; or b) by using an automated schema verification and a semi-automated process where the original JSON schema is extended through purpose-developed context-free grammar, as detailed in [18].

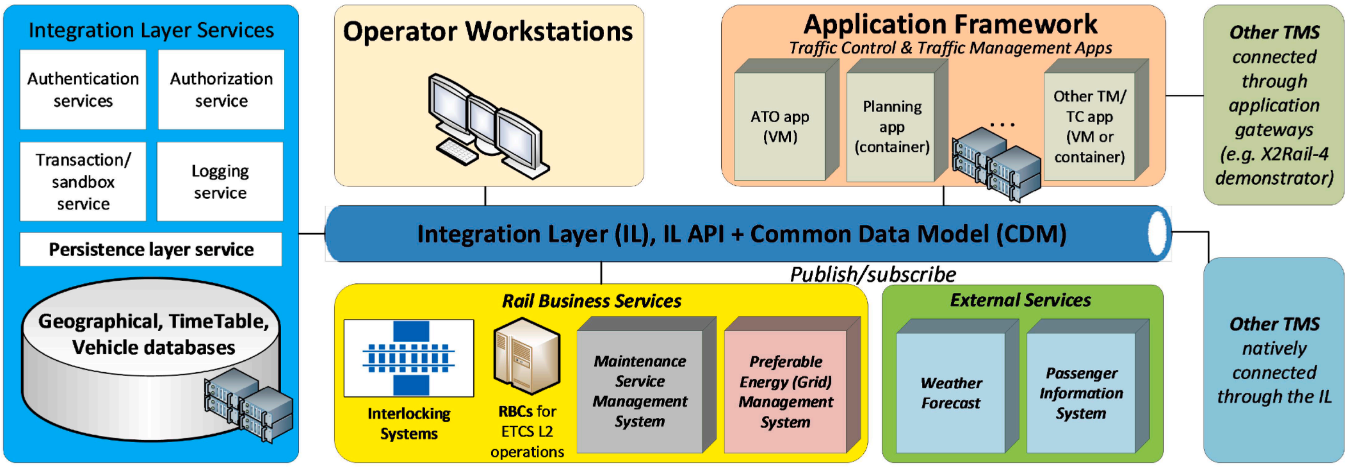

Fig. 1. The architecture of the OPTIMA Communication Platform Demonstrator.

2.2. The Integration Layer

The IL is one of the main components of the OPTIMA CPD since it is responsible of providing the seamless access to persistent data and real-time status data from heterogeneous sources. Furthermore, it allows automated data exchange process, real-time availability of the data and configurable Quality of Service (QoS) levels. The IL uses standardized and interoperable data structures and processes based on the definition of a CDM for the data exchange between different RBS and external services.

The IL is based on a publish/subscribe mechanism and has been developed by using RTI Connext software framework [19], a commercial enhanced implementation of the Object Management Group (OMG) Data Distribution Service (DDS) - a middleware protocol and API standard for data-centric connectivity - and it includes the DDS API and network interoperability protocol. This product was chosen since its characteristics are almost fully compliant (92% of the requirements were fully satisfied while the rest were only partially satisfied) with respect to the requirements foreseen by the OPTIMA project and by the previous In2rail and X2Rail-4 projects, compared to other available frameworks.

The OPTIMA developers have created a specific API to allow the implementation of applications able to access this middleware in a standardized way and compliant with the defined CDM to guarantee the interoperability of the exchanged data. In particular, in addition to a "Core" IL-API which oversees all aspects of communication through RTI DDS and provides all the low-level services for accessing database elements in real-time (such as writing, reading, asynchronous reading, blocking, etc.), higher level primitives have also been provided for operations and functions related to real-time database management, centralized processing, and serialization and deserialization operations according to the used PSM.

To publish data on the IL it is required to 1) call the IL-API codec library to define the structure for the data to be transmitted, 2) copy the data inside this structure and, finally, 3) connect to the IL to transmit the encrypted data. Similarly, when a service intends to read the data of a topic present on the IL it must 1) connect to the IL and subscribe to the topic, 2) wait for the notification of a new data present and in this case 3) decode the data received by calling the IL-API code library.

2.3. Rail Business Services and external services

Three infrastructure managers RFI - (Italy), ADIF (Spain) and SZDC (Czech Republic). RFI provided information on the railway route chosen for the demonstrator (the Ventimiglia-Albenga international line on the western coast of Liguria region in Italy), in particular the topology, information from the Interlocking systems, train timetables, and all the main events that can happen along the railway line. ADIF exported current and observed meteorological data along its network lines, while SZDC provided the status of maintenance operations such as railway closures and restrictions, and the energy status of its network. This heterogeneity of infrastructures, and the cyber security limitations that impede a direct connection to the IMs production systems have led to the definition of a particular architecture (shown in Fig. 2) for the acquisition of traffic-related data. This architecture expects the data from the three IMs to be mapped into a One Virtual Track (OVT), the Ventimiglia-Albenga railway line, using a software called "OVT mapper": the data from the weather stations (from ADIF), from the restrictions on railway traffic and from the state of the electricity grid (from SZDC). All collected data is made anonymous and stored in log files which are processed by the "Player" software to publish on the IL all events according to the recorded timestamps, via the APIs described in Section 2.2.

2.4. The Application Framework and the standardized Operator Workstations

The CPD provides the AF operating environment for plug-and-play installation for TMS and TC software for vendors, system integrators or IMs. The AF offers the possibility of installing this software by means of virtual machines or containers that can be installed by simply uploading their images to the system and subsequently configuring and running them. This possibility allows for a variety of services and micro-services, each in its own standardized runtime environment and isolated from the others, which offer high modularity and reliability also through fail-over and redundancy mechanisms. Among the services offered by the AF are i) resource management to ensure high availability, ii) centralized monitoring and configuration to enable a "system" view on distributed components, and iii) management of networking aspects and safety. The AF is connected to the IL to allow installed services easy access to RBS and external services. In this way, the developers of TMS/TC services, in addition to using standardized interfaces and data structures for data access, have at their disposal a homogeneous environment orchestrated by the AF management software in which the complexity of service management remains hidden. The software used for AF are VMware Vsphere (for virtual machine orchestration and hypervisor) and Docker Swarm (for container management).

Running AF applications can be operated or managed through Operators Workstations available in the Control Rooms, standardized accordingly to the TD2.9, and connected to the IL. These OWs allows a unified vision of all the TMS applications by means of an ad hoc implemented Graphical User Interface (GUI) that lets the operators to

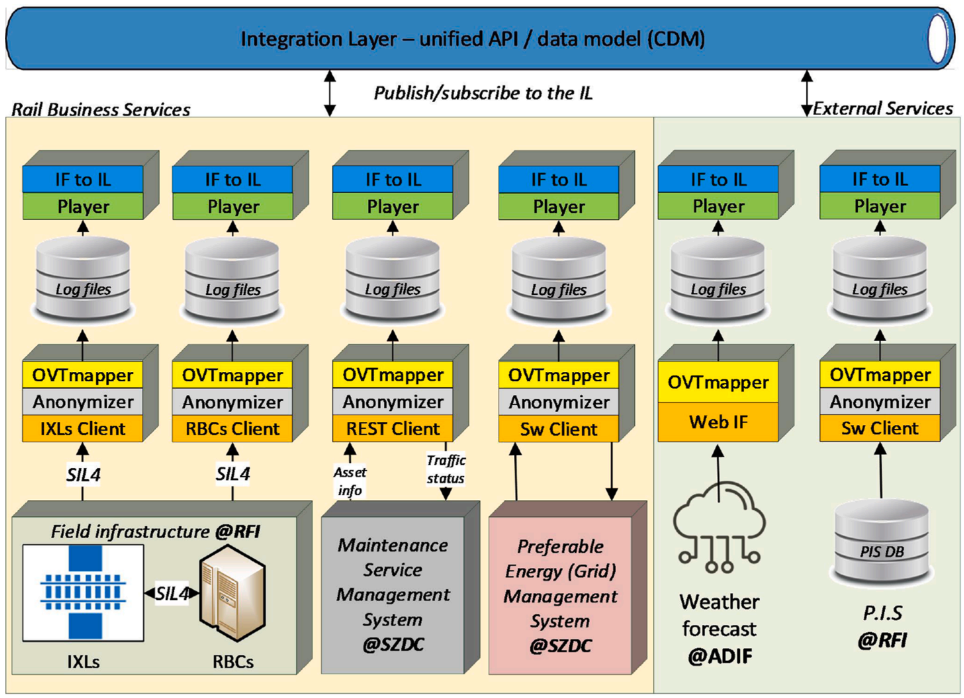

Fig. 2. One Virtual Track for railway field information services.

use any TMS application they are authorised to access.

3. Testing and validation of the OPTIMA Communication Platform Demonstrator

The objective of the testing and validation process is to verify that the OPTIMA CPD developed is functional and feasible as a testing environment for TMS and services that are compatible with, and require a unified communications platform to operate. Furthermore, the testing activities aim to validate the performance of OPTIMA CPD and its subsystems with respect to the aims and objectives of the project, and to requirements of potential end users. This is of critical importance in ensuring and verifying that the project has delivered a system which enables the attainment of the vision for future European Rail Traffic Management with enhanced functionality, efficiency, reliability, resilience, and interoperability, through providing a testing environment for the software components, and contributing to the shaping of the communications solutions.

The testing and validation process within the OPTIMA project consists of two main stages, i.e., (1) the testing of the OPTIMA CPD itself, and (2) the testing of novel traffic management systems and other services developed by industry within the complementary S2R projects. The second stage involves two aspects: one is validating the functionalities of the OPTIMA CPD as a communication platform and testing environment, the other is the validation of the systems and modules from other projects under test.

3.1. Methodology

The general approach adopted on testing and validation of the OPTIMA CDP [20] is shown in Fig. 3 After the analysis of the system requirements and the generation of the KPIs for assessing the test results, the validation activities are organized and prioritized, mapping requirements and KPIs of the whole system into an ordered series of tests and validation targets, and the test scenarios are generated specifying test conditions and processes, which produce the data required for the assessment of the system against the requirements. Then the test are setup (creation, provisioning and configuration of all essential data, interfaces, connections, power-supply, software, hardware, etc.) and executed saving essential log files saved. During the subsequent evaluation of test results, if the KPIs for the system or component/module under test are not satisfied, the tested entity and its test results shall feedback to developers for revisions and updates. Finally, a full validation report created.

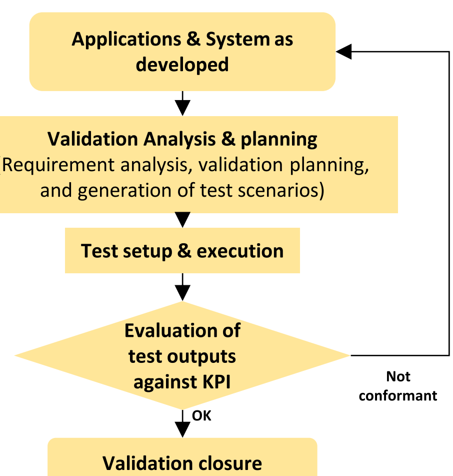

Fig. 3. Testing and validation process.

In some cases, where the characteristics of the system were checked for compliance with the requirements directly, formal testing of the OPTIMA CPD was not required or needed. The requirements for OPTIMA CPD to be considered in the validation process were established from complementary projects, pre-existing standards, railway interoperability requirements, as well as conventions for railway traffic management system, railway operational rules, the communication principle of interconnected sub-systems, etc. The KPIs identified and/or defined for the OPTIMA CPD mainly quantify or/and qualify the QoS of the whole CPD by evaluating the capability and capacity of the demonstrator to receive, prioritise, deliver, and save data supporting railway traffic management systems and connected services. Some example KPIs to evaluate system QoS for the OPTIMA CPD are shown in Table 1.

The requirements and KPIs for the TMS applications and services to be tested in the second stage are based on those determined for those applications and services in the projects they originated from. In this second stage of the validation, further data for the assessment of the OPTIMA CPD against the requirements for the system are generated, as well as data for assessing the performance of TMS applications under test. In addition, the second stage includes testing the specific functionalities and general performance of the OPTIMA CPD to support the validation of novel traffic management applications developed by complementary projects.

In both stages of testing, the OPTIMA CPD is set up to communicate mock and real-time data to simulate railway operations on a section of real railway network modeled in the system. This presents the TMS applications and services with data similar to real-time data on an operating railway network, to enable the responses of those applications and services to be assessed. In some scenarios in the first phase of testing, where the important factors are the speed, accuracy and capacity of communication, the mock data might be abstract data.

This contributes to the wider objective of developing systems in line with the concept of having railway operating systems and services, specifically TMSs, connected to a common communication platform, to enable the improvement of railway operations and services. Furthermore, this makes the communication platform operate as a testing environment for the development and validation of the connected applications and services.

3.2. Internal test programme and procedures

A test programme has been initially developed to plan and organise the implementation of validation activities. The design of the test programme and planning of the tests internal to the OPTIMA project involved specifying the general outline of tests to generate data to assess the performance and characteristics of the system against the requirements, prioritising the tests on the basis if the criticality of the aspects of the performance or characteristics of the system that they would enable to be assessed. Furthermore, a detailed planning of the selected high priority tests was produced.

The internal tests were divided into specific groups based on the component of subsystem of the CPD, or the characteristic or performance criteria of the CPD that were the focus of the tests, as follows:

Validation of the IL to support RBS - Tests primarily related to the ability of the Integration Layer to support communication with the Rail Business Services.

Table 1
Example of KPIs to evaluate system QoS for the OPTIMA Communication Platform Demonstrator.

KPI definition	Description	Expected value
Time to registration	The IL should provide a mechanism for Service Registration. A client application intended to provide a service registers itself at IL.	up to 1s
Mean time between failure	The operating environment hosting the IL, and the middleware part of the IL itself, shall be designed to enable operation 24 h a day, 365 days per year.	as long as possible
Rate of correct routing (%)	The data should be routed to correct provider/consumer. The IL shall route requests to the correct provider, and data to correct consumer: The IL shall be able to route requests and messages to the correct service provider/data source, and the responses to the correct consumer.	100%

QoS - Tests associated with the Quality of Service of the CPD, the capacity and accuracy of data delivered through the CPD, and the promptness with which it arrives.

Validation of IL and IL-API - Tests related to the functionality of the Integration Layer and Integration Layer Application Programming Interface (IL-API)

Validation of RBS communication - Tests associated with the functionality, configuration and connection of the RBSs with respect to their ability to publish the relevant data to the IL.

AF validation - Tests related to the functionality of the Application Framework.

Validation of Operator Workstations - Tests associated with the functionality of the Operator Workstations and Graphical User Interface in terms of subscribing to data topics on the IL and displaying the information to operators.

WEBIF validation - Tests associated with the ability of the CPD to support making data from sources published on the Internet available on the IL, and making information available on the IL publishable to the Internet.

Also, several different types and categories of test were considered, along with the type of testing scenario for each test: a) Functional tests (including Unit, Integration, and System tests), and b) Non-functional tests (including Performance, Security, Usability, and Compatibility tests). Acceptance tests were not considered, being low priority at this stage of development.

The comprehensive test programme has, therefore, defined fifty five specific tests. Considering the target Technology Readiness Level (TRL) 6–7 of the developed CPD, as well as constraints regarding the time and resources available, it was agreed that only the high priority tests would be implemented. Therefore, the tests were assigned a priority for implementation, by using the specific prioritisation MoSCoW method [21]. Each test was assigned one of four levels of priority ranging from the highest priority level of “Must - M”, through the descending levels of “Should - S” and “Could - C”, to the lowest level of “Won't - W”. Fourteen tests that have been considered effectively essential to implement, as they would provide data relevant to validate most of significant aspects of the CPD, have been assigned with the “Must” priority level.

3.2.1. Test scenarios

In the development of the test programme, the types of test scenario which would be used to generate the test data was also considered. The main types of scenarios were running the CPD with data flows representative of operational railway network, and stress tests using large volumes of mock data which did not have any particular meaning. The purpose of the former was to check that the different types of data were handled correctly and that the outcomes were logical. The purpose of the latter was to check the technical capability of the CPD to communicate larger volumes and frequencies of data, where only the correlation of source and output (and the success of any processing) were significant and using large volumes of mock data allowed the testing to be accelerated and the performance of the system under higher loads to be checked. The types of scenarios with data flows representative of operational railway network consisted of a default baseline set of inputs representing a set of operational conditions, and specific modifications to those inputs to represent different operational conditions to check the response of the CPD to specific conditions and that variations in the input were correctly registered by the CPD. Further types of test scenario included checking specific features, sub-systems, or components of the CPD which were not part of the main operational process, such as commissioning and administration of the system. Following the definition of the test programme, the tests were assigned to smaller groups within the project and detailed planning of the individual test carried out. This involved definition of the specific values and parameters to be used to generate the test scenario in the case of the tests representing operational conditions, or the definition of the tools to define the mock data for the stress tests, as well as the output parameters to be monitored and collected, and any expected values, in order to assess the outcome of the test against the requirements and KPIs.

3.2.2. Examples of internal tests and overall outcomes

Two of the fourteen high priority tests carried out for the validation of the OPTIMA CPD are presented further, along with the overall outcomes of the implementation of the test programme, to illustrate the adopted testing procedure. Some tests, by default, had some commonality between them, for example testing if a specific type of data or input was communicated through the CPD would also test if general communication and routing of data was functional.

However, specific tests were intended to focus on specific areas, and other areas with commonality with other tests were not necessarily tested or analyzed exhaustively.

Test 1: Passenger timetable updates The first example, indexed as Test 2.3 in the project, involved the communication of the planned timetable through the IL to the OW/GUI. This test represented operational scenarios in which planned timetables would be changed, such as adding additional trains, or terminating services early along a route due to maintenance work and the output corresponded to the revised input. The test procedure was to run the CPD with the default baseline set of input data, then, while the CPD was running, replace the planned timetable input file with a modified version. The modified timetable included changes to the origins, destinations, departure/arrival times of six trains during the day, amounting to about a hundred timetable event changes. An example of the changes to the input file is shown in Fig. 4, where the original timetable for the train with the ID "10118" in the upper part of the figure is changed to that in the lower part, where it terminates earlier along the route by removing the last timetable events for that selected service.

During this test, the display of the planned timetable on the OW/GUI (which was read from the IL) was observed and logs made recording both information displayed both before the original planned timetable input files were replaced with the modified versions, and after. The analysis of the test consisted of comparing the data in the input files with the logs recorded of the output on the OW/GUI, to check that the data in the output logs was correct with respect to the relevant input file. The data in the files were compared both for the six trains which were modified, and several randomly selected unchanged ones. In all cases the data in the output logs was correct with respect to the relevant input files; this demonstrated that a) the information was correctly written to the IL, b) other applications could read the information from the IL, c) the information was correct and unmodified between source and recipient, and d) when the input files were updated to change the conditions of the scenario, the output corresponded to the revised input. This latter point demonstrated that the system was updating and communicating correctly, and that the outcomes were due to the active communication of data and not due to other circumstances, such as old data being retained in the memory of the receiving application. The results of Test 2.3 contributed to validating the CPD against the identified requirements for it, i.e., to have i) "Rate of correct routing of data of 100%", and ii) "Accuracy of data handling and processing of 99%".

Test 2: Real-time data exchange The second example, indexed as Test 8.1, focused on testing if RBS agents subscribed to external web sources through a Web Interface (WEBIF) could collect data from the WEBIF and write that data to the IL for other applications to use.

The procedure for the test was to independently collect the weather forecast data for each of three different weather stations on each of three different days from the same external web source as it is collected by the CPD weather RBS, but collecting it independently from the OPTIMA CPD, by directly querying the source and write the values to a JSON log file, and compare the values in the log with those displayed on the OPTIMA CPD OW/GUI of the CPD for the corresponding weather stations and days. This test used the default set of inputs for baseline scenario of the test, although the values for the weather forecast obtained from the external source vary each day according to the values predicted by that service, which would provide varied inputs to the test. This tested both the writing of data collected from external sources (in this case through a WEBIF) to the IL, which was the focus of the test, and the reading and display of data from the IL, although in this case the OW/GUI was a tool used to visualise the data on the IL, not the focus of the test. Fig. 5 shows the screenshot of an example of the entry in the JSON log file of the independent method of collecting the data from the source, for one of the days and weather stations, and Fig. 6 shows a screenshot of the OW/GUI for the same day and weather station displaying the same predicted values for the weather forecast. The entry of the value "11" in the "velocidad" parameter field in the red box in Fig. 5, corresponds to the value of "11" in the "Wind Speed Value (km/h)" in the red box in Fig. 6. Similarly, the entry of the value "S" in the "direccion" parameter field in the yellow box in Fig. 5, corresponds with the value of "180" in the "Wind From Direction Value (°)" in the yellow box in Fig. 6, both of which represent a southerly wind direction expressed in different units and languages. Considering the translation and conversion of the Spanish source that uses compass directions to the OW/GUI that uses degrees for direction, the values for the parameters in Figs. 5 and 6 are

DateID	TrainID	DepartureTimeHelp	PasFre	InterCity (Y/N)	Loco/Unit	Station	FN/TN/PN/AN	A_Platform	ArrivalDate	ArrivalTime	ArrDelay
05/02/2020	10118		P	N	Loco	ANDORA	FN	II	05/02/2020	18:04	4.5
05/02/2020	10118		P	N	Loco	DIANO	FN	I	05/02/2020	18:08	
05/02/2020	10118		P	N	Loco	IMPERIA	FN	II	05/02/2020	18:17	4
05/02/2020	10118		P	N	Loco	TAGGIA ARMA	FN	II	05/02/2020	18:26	3
05/02/2020	10118		P	N	Loco	SANREMO	FN	I	05/02/2020	18:29	
05/02/2020	10118		P	N	Loco	BORDIGHERA	FN	II	05/02/2020	18:40	2
05/02/2020	10118		P	N	Loco	VALLECROSIA	TN	II		-	
05/02/2020	10118		P	N	Loco	VENTIMIGLIA	AN	I	05/02/2020	18:48	1.5
05/02/2020	160	17:55	P	Y	Loco	LOANO		I	05/02/2020	17:54	4.5
05/02/2020	160		P	Y	Loco	BORGHETTO S.SPIRITO		I		-	

DateID	TrainID	Departure…eHelp	PasFre	InterCity (Y/N)	Loco/Unit	Station	FN/TN/PN/AN	A_…orm	ArrivalDate	ArrivalTime	ArrDelay
05/02/2020	10143		P	N	Loco	BORGHETTO S.SPIRITO		II		-	
05/02/2020	10143		P	N	Loco	LOANO		II	05/02/2020	18:55	8.5
05/02/2020	10118		P	N	Loco	ANDORA	FN	II	05/02/2020	18:04	4.5
05/02/2020	10118		P	N	Loco	DIANO	FN	I	05/02/2020	18:08	
05/02/2020	10118		P	N	Loco	IMPERIA	FN	II	05/02/2020	18:17	4
05/02/2020	10118		P	N	Loco	TAGGIA ARMA	FN	II	05/02/2020	18:26	3
05/02/2020	10118		P	N	Loco	SANREMO	AN	I	05/02/2020	18:29	
05/02/2020	160	17:55	P	Y	Loco	LOANO		I	05/02/2020	17:54	4.5
05/02/2020	160		P	Y	Loco	BORGHETTO S.SPIRITO		I		-	

Fig. 4. Modification of the train timetable input files in test 2.3.

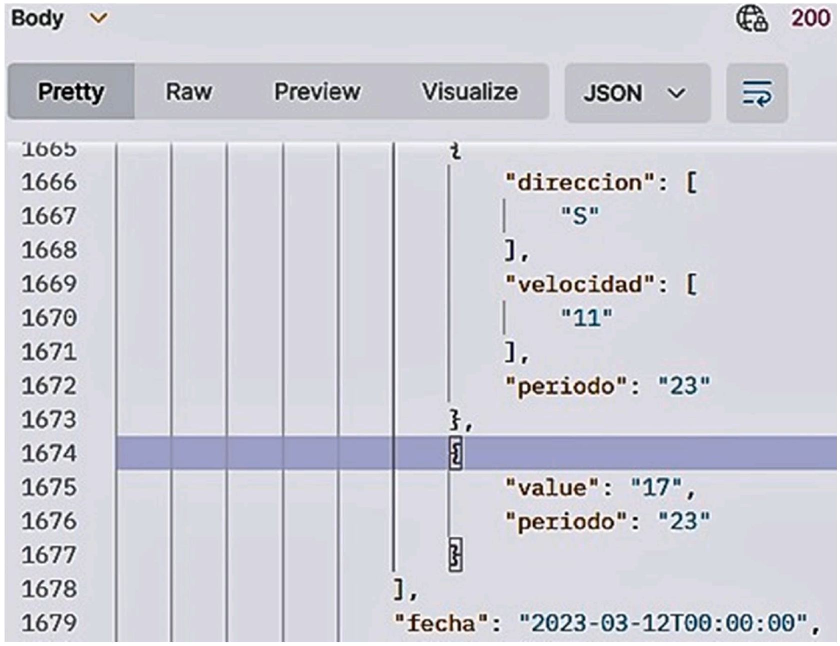

Fig. 5. Example of JSON file in test for validation of WEBIF.

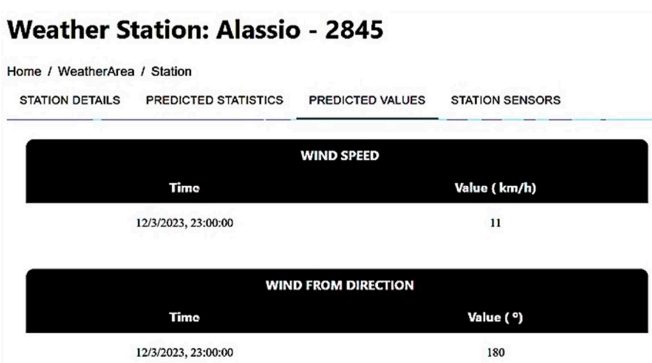

Fig. 6. Example of OW/GUI showing the weather data as displayed.

the same, as they were for the other eight combinations of day and weather station for which the results were collected and assessed. This demonstrated that the CPD RBS correctly read the data from an external web source and wrote it to the IL, where it was subsequently available for the OW/GUI to read the data, validating the CPD against the identified requirement for it to have “high performance web-based communication”.

3.2.3. *Lessons learned*

These two examples of the tests show how the internal testing programme was planned and implemented to provide data for assessing the OPTMA CPD against the validation criteria. The assessment of the performance of the OPTIMA CPD against the KPIs demonstrated the critical functionality and performance of the OPTIMA CPD. This showed that the CPD is technically capable of communicating the types of data representing the flow of data expected to occur in a middleware application for the next generation systems for railway traffic and operations management. However, during the tests, although the CPD was generally functional, there were some issues identified, generally related to the selection of the data to be communicated and the format of the presentation of that data, which might impact specific use cases for the CPD. For instance, in the energy management RBS the data for some of the power distribution areas would stop updating correctly after the system had been running for a certain amount of time. This could lead to the incorrect data relating to the status of the energy supply to trains being communicated by the CPD to a TMS module under tests (making decisions or supporting an operator making decisions based on the outputs of the module), which is not synchronised with the intended scenario. In this case, the TMS module might be working as intended, but the response it gives to the situation being simulated by the CPD could be assessed as being incorrect if evaluated against how it should have functioned with the correct data. For instance, if the CPD is expected to represent a situation where the power supply to a section of track is off, but it is still supplying data to the TMS that the power is on, the TMS might allow an electric train into a section of track which it was told has power (which would be the correct action in that situation), when it was expected not to allow the train into this section. This illustrates the importance of the testing in ensuring that the CPD is functioning correctly, so that the performance of the TMS modules under test can be accurately assessed. In a number of successful tests, the data from the input files was read into the CPD “as-live” correctly, the tests checking the input files against the CPD output, demonstrating effective communication. In the case of the issues with the energy management RBS, a solution was identified, however the project ran out of time to implement and re-test, and similar types of data communication were shown to be working. Although the main objective was to demonstrate its technical functionality, not the suitability for any specific use case, it is expected that the system could be customised for specific use cases. Therefore, the CPD was generally functional, and, since the highest priority tests related to the most critical requirements were implemented, with just some minor issues being identified, the OPTIMA CPD could reasonably be considered as being partially validated after the completion of the first stage of testing (i.e., the internal testing within the project).

3.3. *Collaborative testing with X2Rail-4 complementary project*

In addition to the internal tests, a plan for testing the CPD compatibility with modules developed by industry has been developed and agreed on in close collaboration with the complementary project X2Rail-4. At the end of 2021 the CPD developed in the OPTIMA project was made available to X2Rail-4 project to validate the interoperability of their modules and applications prototypes against the OPTIMA IL and

PSM implementation.

Amending the TD2.9 of S2R it was agreed with X2Rail-4 not to install the prototypes within OPTIMA's Application Framework but to federate the ILs of both projects to build a large-scale demonstrator called "TMS Cloud" (see Fig. 7). This federation has the advantage of using different middleware technologies (DDS in OPTIMA, In Memory Data Grid in X2Rail-4) so as to further verify and validate the interoperability between different systems, and allows maintaining the development of application prototypes within source project.

According to the planned agreement, the federation of the IL of the OPTIMA CPD with the IL of X2Rail-4 demonstrators took place through an IL gateway developed within the OPTIMA project, which allows X2Rail-4 prototypes to connect to the OPTIMA IL and successfully access the OPTIMA CPD resources (i.e., Rail Business Services and databases). To this end, the IL federation was designed by developing a special service, called the *IL-gateway*, running in a container of the OPTIMA AF, that supports continuous communication between the OPTIMA IL and the ILs of the three X2Rail-4 demonstrators (see Fig. 8). This service allows X2Rail-4 prototypes to connect to OPTIMA CPD via Simple Text Oriented Messaging Protocol (STOMP) and publish/subscribe to/in OPTIMA IL, as well as allows OPTIMA TMS applications to publish/subscribe data in/to X2Rail-4 IL by simply using IL-API based on RTI-DDS.

3.3.1. *External tests performed in OPTIMA using the X2Rail-4 gateway*

To validate this architecture, and, in particular, the interoperability of the data structures of the PSM/CDM, the communication provided by the ILs with their APIs as implemented in the two projects, implementing the collaborative testing, specific use cases have been agreed.

The specific use cases agreed between OPTIMA and the X2Rail-4 consortium and tested through the IL-gateway are:

- OPTIMA receives weather information and publishes the data to TMS Cloud;
- OPTIMA receives train status data from the Radio Block Center and publishes the train position on the TMS Cloud;
- OPTIMA receives information from the maintenance management system and publishes the data on the TMS Cloud.

Each use case was defined for specific tests and considered all relevant details, such as: a) a short description of the use case, along with the test case name and group, b) the input data used in the OPTIMA CPD to generate the output of the RBS considered, c) the output data location and format in the server of the OPTIMA CPD, d) the operations on the IL-API needed to be implemented in the IL gateway to access the output data, e) the dependencies and constraints of the use case, f) the test procedure, g) the type of the test result, and h) the expected outcome/validation criteria of the test.

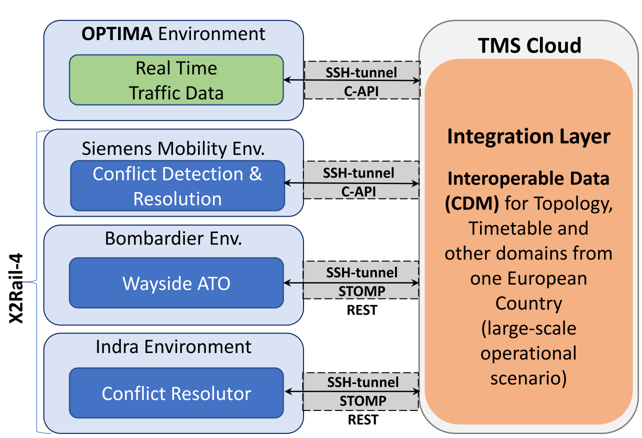

Fig. 7. Architecture of the large-scale demonstrator.

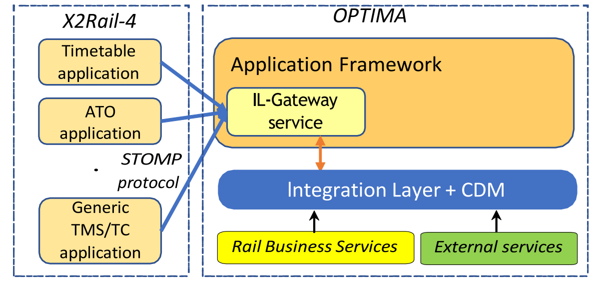

Fig. 8. Architecture of IL-gateway.

Each project has successfully carried out its own integrated test campaign consisting of the execution of different processes and the simultaneous monitoring of the data exchanged.

In OPTIMA the test campaign used specific applications developed by X2Rail-4, executed outside the CPD, which connected to the IL-gateway by means of the STOMP protocol in the same way as the applications and modules normally developed and executed in X2Rail-4. In Fig. 9 is shown an example of the validation of the RBC test case using a testing application connected to the IL-gateway on the external side of the CPD. It shows the current train speed and the speed history, on a mock Operator Workstation display connected to the OPTIMA CPD gateway, populated with RBC data from the CPD.

During this collaborative testing campaign with X2Rail-4 project, the CPD was repeatedly corrected and ameliorated to improve data interoperability and communication reliability. The most significant result of the final version of the CPD thus obtained is that each application or prototype developed in each of the two projects can be executed and verified on the demonstrator with the reasonable certainty that the behavior of these applications complies with a common specification data communication and interoperability. If this specification becomes a reference within Shift2Rail, all actors involved could use it to develop and validate their own TMS applications.

3.4. *Testing and validation summary*

The internal tests demonstrated that the OPTIMA CPD is generally functional and capable of communicating data in the required formats, and with the required performance. The tests with external projects demonstrated that it is interoperable and can communicate with elements of a TMS developed by external parties to follow the same principles of communication through a middleware layer. The success of the testing and validation of the CPD showed that the system satisfied the key requirements, and that the project had achieved its key objectives. The conclusion of the validation activity, which lasted the last 22 months of the project period, allowed the OPTIMA project to reach Milestone 6 of the project set at the project deadline. Achieving this goal is absolutely relevant because it means that the project objective of having functioning and tested the CPD has been achieved. In the future, the testing of the OPTIMA could be extended to include the lower priority tests defined in the project, which were not carried out due to limited resources. Beyond that, there are two main directions of further development and testing which could be explored: a) connecting different TMS modules and data services to the OPTIMA CPD to test that the required data is communicated; b) increase the functionality of the OPTIMA CPD to enable more detailed simulations of operational scenarios to be represented, and to incorporate the output of the TMS modules under test into the operational scenarios. Furthermore, the CPD and TMS modules could evolve in the future based on the outcomes of further rounds of testing TMS, with the potential refinements of the requirements for both based on experience.

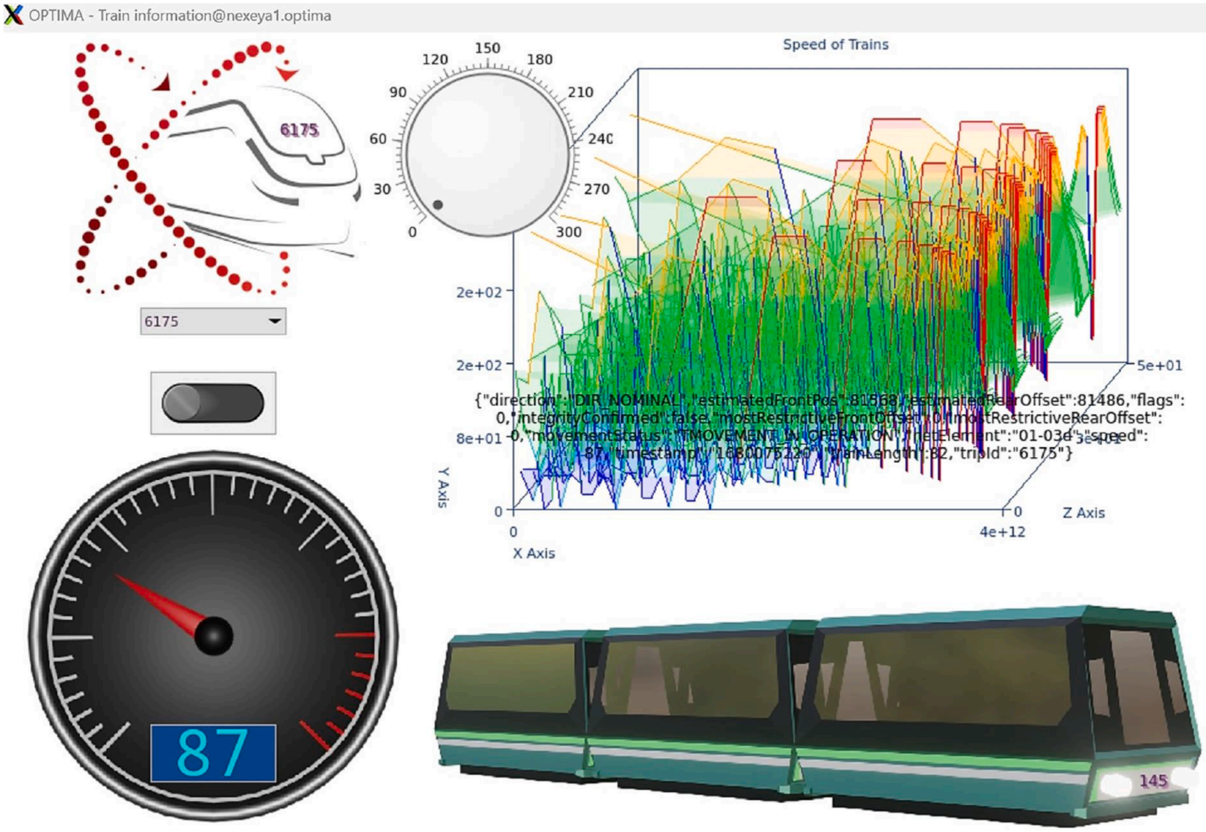

Fig. 9. Testing of RBC service connected through the IL-gateway.

4. Conclusions

This paper illustrates the outcomes of the H2020 Shift2Rail OPTIMA project, the Communication Platform Demonstrator (CPD) for the testing of innovative applications and services for TMS and TC applications. The demonstrator guarantees continuous access to real-time updates and persistent data from heterogeneous data sources of railway tracks with self-external communication and data exchange processes. The architecture of the CPD is based on four constituent elements: 1) the IL, the middleware for real-time communications with standardized interfaces; 2) the CDM which provides a system of standardized data structures for the interoperable exchange of information between different applications; 3) the RBS and external services that provide information on topology, interlocking, RBC, maintenance, energy networks, weather forecasts, and PIS; 4) the AF where services and applications for TMS/TC are installed in a plug-and-play manner and run in isolation within Virtual Machines or containers, with full management and control of the available computing and network resources, and finally 5) the OWs that allow operators to interact directly with the system and through the various application interfaces.

The paper also describes the testing methodology and validation of the OPTIMA demonstrator and the main results obtained. In particular, it illustrates the study and development of the validation program, some examples of tests with their results and the validation of the system when it has been used with applications coming from complementary projects of the S2R program. This last part of the validation program made it possible to further corroborate the interoperability and standardization aspects of the Communication Platform Demonstrator even when it is federated with other systems as part of a larger demonstrator called 'TMS Cloud'. This broadens the objectives of S2R Technology Demonstrator TD2.9 and lays the foundations for the development of TMSs that are no longer limited to the regional or national context but also at the European level. The Technology Readiness Level (TRL) reached by the demonstrator is 6/7 and its future improvements also coming from the current program of Europe's Rail Joint Undertaking could further raise its TRL.

Note that, in perspective, the IL and the CDM will significantly empower the use of Artificial Intelligence (AI) in railway systems by bridging the gap between diverse data sources, sophisticated AI algorithms, and various operational processes. These essential components streamlines the flow of information, enabling seamless communication and data exchange among different subsystems, such as signaling, scheduling, and maintenance. By unifying these disparate elements, the IL facilitates the implementation of AI-driven solutions, such as predictive maintenance, optimized energy consumption, and real-time traffic management. In conclusion, from this point of view the Integration Layer plays a crucial role in unlocking the full potential of AI applications by facilitating seamless communication and data exchange among different subsystems. This results in improved operational efficiency, safety, and customer satisfaction, ultimately driving the railway industry towards a more innovative and sustainable future, transforming the railway industry into a more intelligent, responsive, and sustainable transportation system.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

Acknowledgments

This project has received funding from the Shift2Rail Joint Undertaking (JU) under grant agreement No 881777. The JU receives support from the European Union's Horizon 2020 research and innovation programme and the Shift2Rail JU members other than the Union.

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