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5th SmartRaCon Scientific Seminar - Proceedings

# 5th SmartRaCon Scientific Seminar

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## 5th SmartRaCon Scientific Seminar

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Institute Director:
Prof. Dr.-Ing. Michael Ortgiese

# Preface

Dear reader,

you are holding the newest volume of the series „Reports of the DLR-Institute of Transportation Systems" in your hands. In this series we publish fascinating scientific research results from our Institute of Transportation Systems at the German Aerospace Center (Deutsches Zentrum für Luft- und Raumfahrt e.V. - DLR) and its collaborating partners.

With this series we communicate results of our scientific work in the fields of automotive, railway systems and traffic management. We hope to enable a broad access to scientific work and results for the national and international scientific community and practitioners in the field of transportation. Beyond that, researchers in the early phase of their academic career of our staff and external doctoral candidates are offered the opportunity to publish their dissertation. In addition, the publication includes outstanding scientific contributions and project reports as well as proceedings of conferences in our house with different contributors from science, economy and politics.

The current volume contains the proceedings of the fifth SmartRaCon Scientific Seminar (SRC5SS), which has been held on May 25th, 2023 in Berlin, Germany. This SmartRaCon Scientific Seminar was hosted together by GMV from Nottingham, UK and DLR aiming to bring together researchers and experts from different railway research areas with focus on technologies like adaptable communications, digital maps, safe train positioning and moving block as well as procedural innovations like zero on-site testing, cyber security and formal methods. The seminar was a vivid and fruitful forum for the presentation and discussion of new and on-going research. As the fifth and last seminar convoying the X2Rail-Projects it is marking the completion of the Shift2Rail program and the handover to the starting Europe's Rail program.

We wish you an interesting and inspiring reading!

Prof. Dr.-Ing. Michael Ortgiese

## All contributions have been double refereed as abstract and full paper by the International Scientific Committee

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Dr. Insaf Sassi (IRT RAILENIUM, Famars, France)

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The 5th SmartRaCon Scientific Seminar (SRC5SS) was hosted together by
GMV, Nottingham, United Kingdom and DLR, Berlin, Germany

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Dr. Jaizki Mendizabal (CEIT, Donostia / San Sebastián, Guipúzcoa, Spain)
Dr. Terri Richardson (GMV UK, Nottingham, United Kingdom)

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# 1 Towards integrated digital automatic train operation – the perspective by SmartRaCon

*Marion Berbineau; COSYS, Université Gustave Eiffel, IFSTTAR, Villeneuve d'Ascq, France*
*Michael Hutchinson; GMV-UK, Nottingham, United Kingdom*
*Emilie Masson; IRT RAILENIUM, Famars, France*
*Jaizki Mendizabal Samper; CEIT, Donostia / San Sebastián, Guipúzcoa, Spain*
*Michael Meyer zu Hörste; DLR, Braunschweig, Germany*

## 1.1 Smart Rail Control Systems - SmartRaCon

Innovative automation and digitalization technologies enable new approaches for train control, command and signaling systems and lead to completely new concepts. The partners RAILENIUM, GMV-UK, CEIT and DLR founded the consortium Smart Rail Control (SmartRaCon) to develop new concepts, approaches and technologies for the train control, command and signaling systems of the future in the frame of the European Programme Shift2Rail. In this contribution, the developments in the areas of Adaptable Communication, Moving Block, Train Positioning, Environment Perception, Digital Maps, Formal Modelling and Laboratory Testing are covered.

Figure 1-1: SmartRaCon Logo

SmartRaCon consortium has been actively involed in a number of Shift2Rail research project since 2016, where the X2Rail series projects can be highlighted. In this context, in the frame of the two projects TAURO [1] and X2Rail-5 [2], SmartRaCon aimed to work on design and development of technology for automation especially in the following fields:

- Adaptable Communication Systems (ACS)
  - Laboratory testing environments
  - On field (Regional demonstrator) characterization tool

    - Satellite Communication
- Fail-Safe Train Positioning (FSTP)
    - Key Performance Indicators and Analysis Tools
    - Ground truth and validation tools
    - Railway infrastructure network representations
- Moving Block (MB)
    - Description of use cases and specification
- Zero on-site Testing (ZOST)
    - Adaptable Architecture of the Lab test bench including Safety requirements
- Digital Maps
    - Data models
- Environment Perception
    - AI-based strategies
- Remote Driving and Control
    - Video and sensors streaming
- Formal Modelling
    - Guidelines for the Railway Signalling Domain
- Cyber Security
    - Cybersecurity Risk Assessment methodology

The overall concept is based on developing novel analyses and tools required for the development, validation and certification, with the idea to reuse COTS and integrating them into a railway network in a modular way. This allows, on the one hand a flexible scaling of the rail control system in a cost-efficient way, and on the other hand a building block approach for certification and modulewise change of technology.

## 1.2 The methodology

Smart Railway Control (SmartRaCon) aimed to be the core to enable high capacity and cost-efficient rail systems for the next century. The proposed approach of SmartRaCon is to control smartly intelligent, autonomous trains on a scalable and more flexible infrastructure. Main challenges for the rail system are the enhancement of capacity, the reduction of investment and operations cost. The reductions of energy consumption as well as the reduction of cost for test and certification are two aspects for the cost reduction. These are the conceptual objectives of SmartRaCon [3] and are coherent with the Master Plan topics of Shift2Rail [4]. The SmartRaCon idea for a credible, coherent and long-term approach to achieve the Master Plan Objectives is to meet those challenges by:

- intelligent trains, which communicate safely & securely, localize & supervise integrity autonomously and operate as virtual coupled train-sets;
- infrastructure which is flexible, easy & fast to configure, less fixed (e.g. wired) & scalable, communicating safely & securely with trains and operating them in moving block;
- traffic management system operating both with optimization algorithms;
- supported by cost-efficient process for design, test and certification which uses highly automated test labs to avoid on-site tests based on formal test specifications.

For the capacity increase, an integrated Moving Block (MB) and Automatic Train Operation (ATO) system has to be implemented. Further technologies are needed as enablers: Fail-Safe Train Positioning need to determine safely & securely in real-time to the trackside train control and Traffic Management System (TMS) together with the support of Digital Maps. Positioning and Adaptable Communications are ensured by combining different technologies. Envrionmental perception is needed, too, to ensure safe and highly automatic operation with remote operation as addition for fallback and specific situations. At the end, everything needs to be secure against cyber attacks which is realized among others by an ISAC. The approach is fully in line with the standardized European Rail Traffic Management System (ERTMS) and the European Train Control System (ETCS) and enhances interoperability. New functionalities & technological solutions require being formally specified and tested. Hence testing needs to be automated & moved from on-site to lab. This achieves the objectives of reliability, improved standardization, lower costs & simplified processes. This prioritization is justified since traffic management, positioning and communication are enabling technologies that need to be tested and certified. The complementary work in areas as e.g. moving block and decentralized interlocking technologies extends the concept to reach a significant and sustainable effect on capacity & cost.

## 1.3 Technological research areas

The overall SmartRaCon concept is based on technology-independent adaptable train-to-ground, gound-to-train communications resilient to radio technology evolution, ensuring safety levels for GNSS-based on-board positioning and train integrity supervision. Some of the most relevant areas of SmartRaCon technological research are shown in Fig. 1-2 and the conceptual groups part of the 5th SmartRaCon Scientific Seminar (SRC5SS) "Automatic Train Operation (ATO)", "Adaptable Communication", "Moving Block", "Fail-Safe Train Positioning", "Digital Maps" and "Cyber Security" as well as procedural innovations like "Formal Modelling (FM)" and "Zero On-Site Testing (ZOST)" coming from the projectcs TAURO [1] and X2Rail-5 [2] and are discussed below.

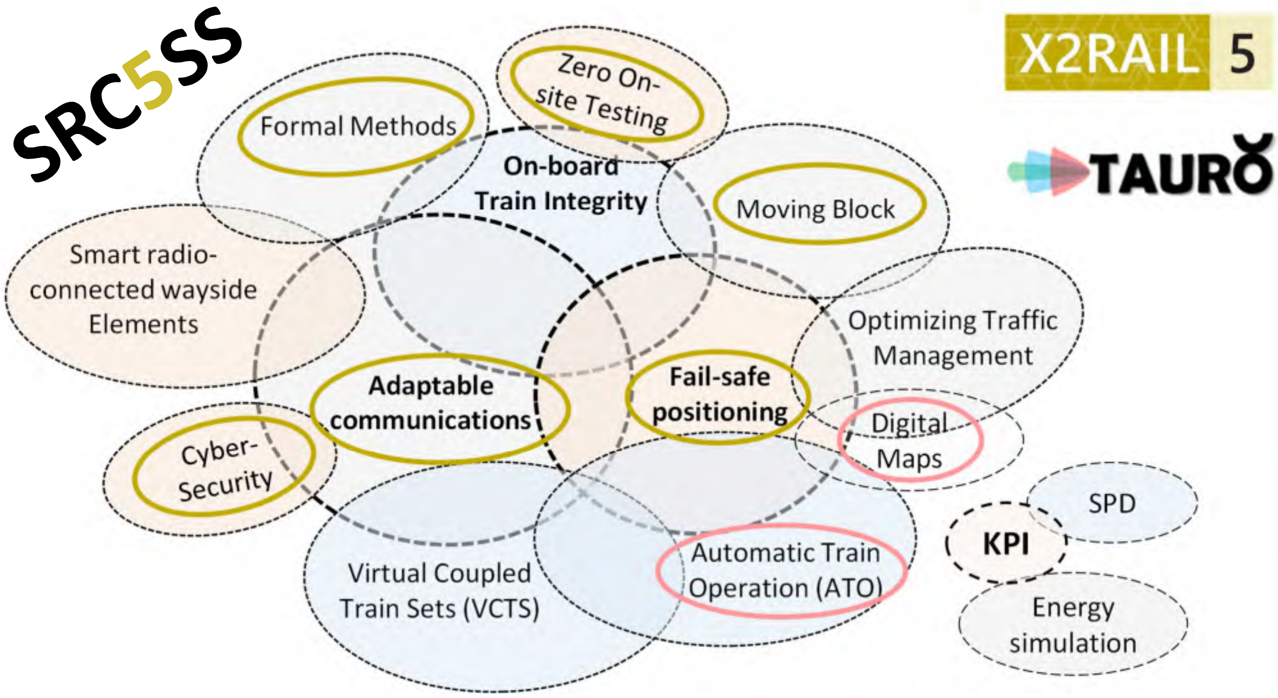


Figure 1-2: Core Areas of Research in SmartRaCon and related projects for the SRC5SS

In the following sections details of each of the conceptual groups and procedural innovations refered are shown.

### 1.3.1 Conceptual group "Adaptable Communications"

The contribution from communication is based on the idea to reuse COTS and to integrate them into a railway network. For that, SmartRaCon will design and develop a technology-independent system for an adaptable train-to-ground communications system resilient to radio technology evolution considering threats such as interferences or cyber-attacks. Some of the concepts to be explored are a) the anticipation of the 5G standardization; b) Software Defined Networks (SDN) and Network Function Virtualization (NFV); c) radio system KPI evaluation; d) hardware development using Software Defined Radio (SDR) platforms, e) IP-based communication gateway with bandwidth aggregation, dynamic spectrum allocation and mobility support; f) traffic pattern recognition tool to ensure minimum conditions; g) innovative use of satellite communications technologies.

The impact for future communication infrastructure relying on standardized technologies and COTS products is high for the European railway, telecom and space industry as well. The use of satellite communications is especially relevant for railway lines, where the availability of a reliable communication infrastructure is critical. By using cognitive radio systems maximum use of surrounding infrastructures will be achieved. Through the use of cognitive radio, 5G, satellite and adaptable, resilient architecture CAPEX will be reduced and moreover IP communication technology supporting a fast radio technology evolution will reduce OPEX.

Current radio technology, i.e. GSM-R, will become obsolete by 2030 and therefore 4G is being analyzed. 5G is already planned to be commercialized by 2020, which will limit the life-cycle of a 4G-only solution. The main advance relies in the ability to successfully integrate a number of heterogeneous technologies and communication protocols into one network in order to take advantage of various deployments (3G, 4G, 5G, Satellites) provided by external network operators (Network as a service) and/or dedicated infrastructures (Network as an asset). Thus, CAPEX and OPEX of communication systems can be minimized. Smooth migration will be enabled by designing middleware platforms for transparent switching radio components.

Impacts on the infrastructure, line capacity and definition of certification processes will be made thanks to the future communications and on-board positioning.

Among SmartRaCon activities there are wireless communication antenna integration, SDN-based slicing and network resource distribution and channel charactersation tool communication system testing.

## 1.3.2 Conceptual Group “Fail-Safe Positioning”

The overall concept for localization is based on the need to ensure that the safety levels provided by existing signaling systems are not compromised when a train-borne positioning system is employed. SmartRaCon has set up and undertaken test campaigns, analyzed the data from such campaigns, improve specifications, provided inputs to the development of a safety case, as well as making other more specific contributions building on the positioning technology expertise within the consortium such as simulation based KPI evaluation, multi-constellation, sensor integration, etc.

In terms of impacts of localization, future business will be generated. A core of safety expertise concerning the use of train-borne positioning technology for railway applications will be established. A Route Clearance service will be used to safely introduce the technology to specific new lines and applications. SmartRaCon will bring an important support to the involved supply chain by developing and certifying dedicated hardware, algorithms and the infrastructure required to deliver the services. The impact will be the contribution to the optimization of global railway operation by providing very efficiently all the needed information to facilitate decision-making process at different stakeholder levels (engineering, exploitation, maintenance, customer services, etc.). Such systems will achieve decentralized control of remote track-side objects without cable connections.

Testing processes and the route to acceptance of GNSS and associated technology will be enhanced such that standardized methods are set in terms of the equipment used, measurements made, analysis tools and results delivery (Route Clearance service, simulation tools for railway KPIs evaluation, Digital Route Maps (DRM)). A consolidated set of specifications and a methodology for testing COTS equipment capabilities will be defined. The need for lab simulations will be identified and a 3D Local Environment Model will be developed. Performance optimization will be proposed through hybridization of GNSS with inertial sensors, odometry, dead reckoning, DRM and Wireless Communications Technologies. Further specific proposed tasks are related to the Safety assessment.

## 1.3.3 Conceptual Group “Digital Maps”

Automatic and digital operation of railways is unavoidably based on very precise and highly safe localization of trains with respect to the railway infrastructure. This raises the need of highly accurate but formal description of the railway network in the form of a digital map. Architectures, concepts and data models of those highly formal and safe digital maps on of the focus topics, too.

### 1.3.4 Further Conceptual Groups

The three above mentioned conceptual groups are related to many others in the context of future systems. Some examples are given below and visualization is given in Fig. 1-2:

- Moving block operation requires safe localization and train integrity as well as reliable as well as adaptable communication.

Automatic Train Operation (ATO) requires environment perception to ensure that trains can run in higher grades of automation. Especially in unattended operation in grade of automation 4 the preception is needed to enable the train to operate. Finally, the dramatic development in the field of Artificial Intelligence (AI) will have major impacts on the railway's ecosystem, too. There are already a lot of applications from scheduling up to condition monitoring as well as many different optimisations. Nevetheless, a massive multiplication of those applications can be expected in the near future.

### 1.3.5 Procedural innovations

Procedural innovations listed in section 1.2 are described as follows:

- Zero On-Site Testing (ZOST) aims to improve standardization and integration of laboratory testing methodologies reducing time to market and improving effectiveness in the introduction of new signalling and supervision systems. Due to the complexity of signalling systems and the differences between specific deployments, a large number of tests are required to be carried out on-site. It is considered that on-site tests take about 5 to 10 times the effort compared to similar tests done in the laboratory. Reduction of on-site tests for signalling and telecom systems is hence the way forward to reduce testing costs. Moreover, and adding more complexity to the process, procedures of verification & validation testing might differ in differnet countries around Europe. Overcoming these differences by standardizing the procedures and test scopes will improve the interoperability and reduce the time to market.

  Activities related to Zero On-site testing include new functionalities to complete the general test architecture, generic communication model between the different components of the test environment(s) defined, standardized interfaces between the products from the test environments of different suppliers and operators and between the test environments and the subsystems under test, simulators to support automated testing in the laboratory. Among SmartRaCon activities there are tools for safety testing of ETCS radio communication link at laboratory and test architecture to integrate operational data related to the driver's actions.

- Formal modelling helps to describe use cases as well as specifications in a coherent and consistent way. Hence, they are the core of a formal description of the railway assets, functionalities, dynamic behavior and condition state. By bringing this approach to a consequent level, a digital twin environment will be realized and used as a complete digital representation of the entire system from high-level socio-economic aspects down to detailed technical as well as functional descriptions.

## 1.4 Outlook for the Europe's Rail JU in Horizon Europe

The research work for future mobility management multimodal environments, digital automated up to autonomous train operation and digital enabler in the frame of the Eruope's Rail Joint Undertaking is taking over results from many projects from Shift2Rail, especially from TAURO and X2Rail-project series [1, 2, 5, 6, 7, 8]. The results of all the work are paving the way for demonstrations in higher technology readiness levels. This Rail European Partnership will focus on accelerating, with an integrated system approach, research, development and demonstrations of innovative technologies and operational solutions (enabled by digitalization and automation) for future deployment to deliver on European Union policies towards "European Green Deal" objectives "a Europe fit for the digital age", "an economy that works for people" and "a stronger Europe in the world"[9].

Europe's Rail will implement an ambitious research and innovation programme, designed in line with the Sustainable and Smart Mobility Strategy, and delivered by the System and Innovation Pillars, bringing the most advanced technological and operational solutions to rail. Steered by an integrated system approach, implemented with a multi-annual programme enabled by the JU's Members, the new Programme will start delivering major flagship solutions as from 2025-26 to be demonstrated at large scale in the following years, and to bridge the future activities in the post-2028 era [13]. Among the innovation topics that would be covered there are the evolution of operational and business aspects such as:

- Configuration of the new European reference operations framework and architecture for Control, Command and Signalling (CMS).
- Future evolution of the ERTMS system.
- Advances in telecommunications (5G developments with specific railway service and business use cases).
- Traffic management platforms.
- Automation of logistics chain, terminals and freight operations.
- Intelligent rail asset management and maintenance.
- BIM development for use in digital rail twins.

## 1.5 Conclusions

The SmartRaCon Partners are performing research work on innovative technologies for Digitalization and Automation to prepare the ground for new generations of train control and railway management systems. Some of the core elements are technologies covered in the 5th SmatRaCon Workshop 2023 topics, namely Adaptable Communication Systems, Fail-Safe Train Positioning, Digital Maps, Automatic Train Operation, Moving Block, and others linked to the both projects TAURO and X2Rail-5. In parallel to the technological research, SmartRaCon Partners are developing and operating simulators and research infrastructures as well as carrying out analyses for the validation of the technologies.

To disseminate the results of the scientific work, SmartRaCon organizes the yearly Scientific Seminars to present and discuss their results on a high scientific level. The first SmartRaCon Scientific Seminar took place on the 25th of June 2019 in Villeneuve d'Ascq in France [10] in presence. Due to the pandemic situation in Europe, the second seminar was held the 24th of November 2020 in a digital online format from San Sebastian in Spain [11]. The third seminar, in the #EUYearOfRail, on the 2nd of September 2021 from Braunschweig in Germany again online [12]. The fourth SmartRaCon Scientific Seminar took place the 20th October 2022 in Donostia/San Sebastian, Gipuzkoa, Spain [13]. Finally, to close the SmartRaCon Scientific Seminars in the frame of the Shift2Rail programme, the fifth SmartRaCon Scientific Seminar will be hosted by GMV and DLR together and takes place in May 2023 in the DLR facilities in Berlin-Adlershof, Germany.

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Europe's Rail

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## 1.8 Authors

Dr. **Marion Berbineau** received the Engineer degree from Polytech'Lille (France) and the Ph.D. degree from the University of Lille, both in electrical engineering, respectively in 1986 and 1989. She is a full time Research Director at Université Gustave Eiffel in the Component and SYStem department and in charge of coordination of Railway R&I activities of the University. She is associated researcher at LEOST laboratory. She is expert in the fields of radio wave propagation in transport environments (particularly in railway tunnels and high speed lines), electromagnetic modeling, channel characterization and modeling, MIMO, wireless systems for telecommunications, cognitive radio for railways and GNSS localization-based system for ITS particularly for the rail and public transport domains. She is responsible for Railway research coordination for the Institute. She is active as an expert for the GSM-R and future systems like LTE-A or 5G NR and beyond 5G. She is involved in several National and European research projects. She is author and co-author of several publications and patents. She is expert at the French national council for the railway system. She was on the reserve list of the Scientific Council of Shift2Rail.

*E-Mail: marion.berbineau@univ-eiffel.fr*

**Michael Hutchinson** has over 14 years of experience in the GNSS industry. Michael has developed solutions for and provided consultancy on a wide range of GNSS applications involving robust and reliable positioning and navigation. This includes aviation approach operations, liability critical automotive programmes, future train control systems and Unmanned Aerial Vehicles (UAVs). Michael also provides consultancy on GNSS system level topics. Michael currently works as International Business Development Manager at GMV-UK, coordinating business development activities outside of the UK. E-Mail:

E-Mail: michael.hutchinson@gmv.com

Dr. **Émilie Masson** is a Project coordinator at Railenium, France. She received the Engineer degree from the Institut Supérieur de l'Électronique et du Numérique, Lille, in 2005 and the PhD degree in electronics from the University of Poitiers, in 2010. She joined Railenium in 2014 as a researcher. She conducted research activities related to telecoms on various European and national projects. She then moved on to become a project manager. Since 2017, she has been coordinating the TC-Rail project, related to railway remote driving, and DRAISY and Tli projects related to light trains. She also coordinates all Railenium activities on Shift2Rail IP2 since 2016.

E-Mail: emilie.masson@railenium.eu

Dr. **Jaizki Mendizabal** received his M.Sc. and Ph.D. degrees in Electrical Engineering from TECNUN (University of Navarra, San Sebastián, Spain) in 2000 and 2006 respectively. He joined Fraunhofer Institut (Nuremberg, Germany) and SANYO Electric Ltd, Japan as RF-IC designer. Nowadays, he is at CEIT, in San Sebastián (Spain) where his research interests include communications and electronic systems for transport systems. He is lecturing "Communications via Radio" at TECNUN (University of Navarra).

E-Mail: jmendizabal@ceit.es

Dr.-Ing. **Michael Meyer zu Hörste** holds a PHD in mechanical engineering from the technical University of Braunschweig. He has joined DLR Institute of Transportation Systems in 2001 bringing already 6 years of railway research experience with him. He is expert in railway operations, command, control and signalling systems, especially ERTMS/ETCS as well as train localisation. Currently he is working the business development of the DLR Institute of Transportation Systems He was a major contributor in building the DLRs ETCS test laboratory RailSiTe®. He is chairman of the ERTMS Reference Labs Association since 2012. He is fellow of the Institution of Railway Signalling Engineers (FIRSE) since 2012. He is member of the Shift2Rail and Europe's Rail governing boards and coordinator in the DLR for Shift2Rail.

E-Mail: Michael.MeyerzuHoerste@dlr.de

# 2 Paving the way towards digital, automatic Rail Operation: The TAURO and X2Rail-5 contributions to the CCS-Systems of Future

*Javier Goikoetxea, Construcciones y Auxiliar de Ferrocarriles, S.A. (CAF), Beasain, Spain*
*Michael Meyer zu Hörste, DLR, Braunschweig, Germany*

## 2.1 Introduction

One major focus of the European Joint Undertaking Shift2Rail is the evolution of the European Signalling and specifically the fully automatic and up to unattended train operation [1, 2]. The aim is to prepare the way to higher degree of automation and to show elements of digital rail operation. While the demonstration of the higher grades of automatic train operation are subject of the project X2Rail-4 [3] the work auf TAURO is focussed on technologies required to complete the automatic operation such as environment perception, remote driving and command as well as further technologies to support the migration [4]. X2Rail-5 supports in the wider view of digital operation with technologies such as fail-safe train positioning, adaptable communication, moving block, cyber security and further [5]. Both projects are ending in the last in last year of the Shift2Rail programme and hence preparing the handover the Europe's Rail Joint Undertaking and the related programme [6]. The logos of both projects are shown in Fig. 2-1.

Figure 2-1: Logos of TAURO and X2Rail-5

Both projects are supporting the multi-annual programme of Shift2Rail and the related targets of improving the reliability of the operation leading to higher punctuality, optimise the use of capacity of the infrastructure and reducing cost [1, 7].

## 2.2 Objectives

### 2.2.1 Overall Objectives

Automation and digitalisation of rail operation is subject of two of the innovation programs (IP) of the European Joint Undertaking Shift2Rail: The IPX is focussed on disruptive technologies as well as the integrated systems approach taking into account the rail automation as a "system of systems" which requires a holistic view of the different technical and procedural elements of the rail system as infrastructure, vehicles, staff, operations and processes as well as regulation and standards. The IP2 "Advanced Traffic Management & Control Systems" is focussed on control-command and signalling systems (CCS) and their related techologies, as e.g. communication, localisation, moving block, etc. The main challenge is to improve the functionalities of signalling and automation systems as well as the related design and validation processes. Nevertheless, the backward compatibility to the existing European Rail Traffic

Management System (ERTMS) and especially its European Train Control System component (ETCS) shall be maintained.

The project TAURO aims to "identify, analyse and finally propose suitable founding technologies for the future European automated and autonomous rail transport, to be further developed, certified and deployed through the activities planned for the European Partnership for Transforming Europe's Rail System" [4]. The technical content of TAURO is organised in four technical work packages, which all are contribution to the goal of the project by separate system elements:

- As the reliable awareness of the situation around a train as e.g. detection and classification of obstacles or the identification of signals the is most important aspect to start a train movement the Environment perception for automation is on the core topics.
- For unclear or unexpected situations or degraded modes it is important to get trains to operation again. Therefore, the approach for Remote driving and command is another key element for automatic operation.
- To support the automatic operation optimally an enhanced Train Control and Monitoring System (TCMS) is most helpful. It is enabled to perform Automatic status monitoring and diagnostic for autonomous trains in order to complement the train's onboard functionality.
- Further Technologies supporting migration to ATO over ETCS which are required to ensure that the specification is complete e.g. for non-ETCS areas as well as ensuring the stable interaction with the Traffic Management System (TMS).

The project X2Rail-5 has been set up in order to conclude activities in six of the eleven so-called "Technical Demonstrators (TD)" in IP2 as well as to provide an Integrated Technical Demonstration (ITD). The actions to be undertaken in the scope of the project are related to the following specific objectives [5]:

- "To improve line capacity and to achieve a significant reduction of the use of traditional train detection systems by means of the introduction of the Moving Block together with train positioning, train integrity and train length;
- To overcome the limitations of the existing communication system by adapting radio communication systems which establish the backbone for the next generation advanced rail automation systems;
- To achieve a significant reduction of the use of traditional train detection systems by means of the attainment of an absolute and safe train positioning system based on a multi-sensor concept, where GNSS is the preferred technology;
- To ensure security among all connected signalling and control systems by developing new cyber security systems dedicated to railways;

- To improve standardization and integration of the testing methodologies and formal methods application reducing time to market and improving effectiveness in the introduction of new signalling and supervision systems;
- To ensure the evolution and backward compatibility of ERMTS/ETCS technologies, notwithstanding of the required functional enrichment of the future signalling and control systems."

The technologies foreseen in X2Rail-5 will bring to the highest readiness level (TRL) taking the results of previous projects e.g. from the other X2Rail-Projects.

In order to show the integrated approach an Integrated Demonstrator is part of X2Rail-5, too. It integrates among others the following results:

- Moving Block (MB) for an urban use case from X2Rail-5
- An on-board train integrity monitoring system (TIMS) from X2Rail-4
- The switch between different radio bearers by the adaptable communication system (ACS) from X2Rail-5

The overall concept of the three projects as well selected relations are shown in Fig. 2-2.

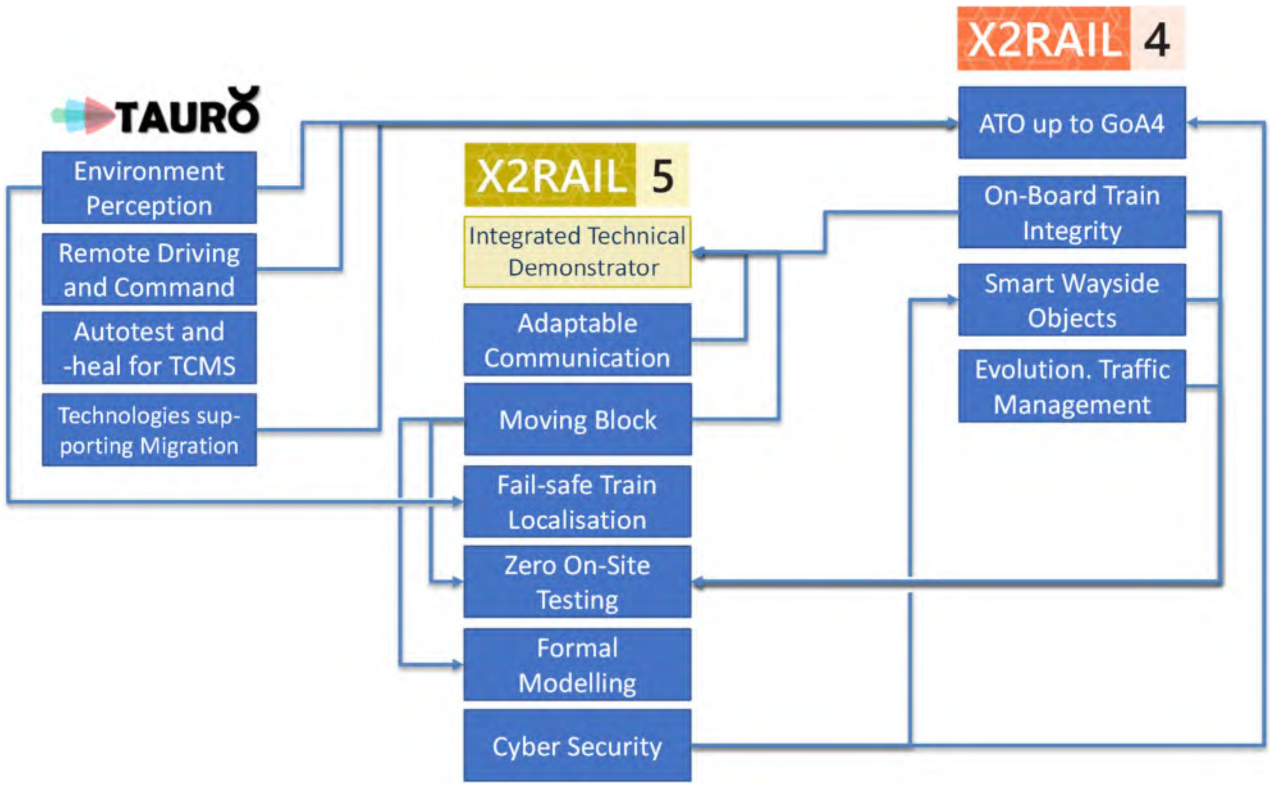


Figure 2-2: Selected Relations between TAURO, X2Rail-4 and X2Rail-5

The Key Technologies appearing in Fig. 2-2 are further described in the sections below including the number of the Technical Demonstrators (TDx.y) in the Shift2Rail multi-annual action plan is provided to show how the work done relates to the Shift2Rail programme [2]:

### 2.2.2 Remote Driving and Command

For different application such as tramways of mainline freight locomotives and different applications like e.g. yard shunting, depot movements or degraded situation in ATO is remote driving and command used to complement the automation of operation. In the WP2 of TAURO the related specification and architecture is developed and a new application profile (use case) will be proposed for the standard IEC/EN 61375-2-6.

### 2.2.3 Automatic status monitoring and diagnostic for autonomous trains

For higher automation especially for unattended operation in Grade of Automation 4 (GoA4) the complete functionality of the vehicle must be enhanced to ensure undisturbed operation. So, the Train Control and Monitoring needs to be enhanced, too. In WP3 of TAURO the related requirements are specified. The requirements are related to the automation of the diagnostics, the recovery and heal or degraded operational mode functionalities, which are needed to optimize the operational availability especially in GoA4.

### 2.2.4 Environment Perception for Automation

The sensing of outdoor as well as indoor environment is topic of the TAURO WP 1 with specific objectives: While the outdoor perception is required for the supervision of safe movement of the train and hence aims to identify potential obstacles as well as the relevant signal status the indoor sensing is focussed on event detection, operational safety, on-board security and overall service quality.

Especially with respect to the outdoor perception the development aims to prepare the system to sense and detect objects, prepare the system for classification e.g. with landmarks and further signatures database and develop a demonstrator in order to assess the performance. A new certification concept is part of the work, too.

### 2.2.5 Fail-Safe Train Positioning

The need of an information of the safe real-time position of the train is an almost ubiquitous requirement for many functionalities in automation of train operation. So, it is present in TAURO in WP1 as well as in X2Rail-5 in the work packages WP5, WP6 and WP7. The fail-safe standalone train positioning solution is the subject of four different test and demonstration activities on different lines in Europe in WP7 in X2Rail-5 as well as topic in TAURO WP1. The focus is besides the functional test on the certification of those solutions. A different architectural approach has been followed in the WP6 of X2Rail-5 with the "Virtual Balise" concept. This will be demonstrated and tested on two lines in different locations in Europe and in a third test in a lab. The WP5 is ensuring the coherent roadmap and migration strategy for both approaches.

### 2.2.6 Adaptable Communications

Current communication concepts are suffering from several drawbacks, e.g. in adapting to different communication environment conditions and requirements. Therefore, the objective of "Adaptable Communications for all Railways" (TD2.1 / WP 3) is to demonstrate that a new

Communication System (ACS) will be able to overcome the known drawbacks and deliver an adaptable communications system that can be used for train control applications in different market sector environments. The basic idea is to bring all the different radio access technologies – e.g. GPRS, EDGE, LTE, WiFi, Satellite, etc. – into a bearer independent solution of IP-based technology. Based on the specifications, guidelines and technology from the projects X2Rail-1, and X2Rail-3 different demonstrators will be shown as well as support the update of the business case study.

### 2.2.7 Moving Block

Several technical demonstrators shall be developed in the field of Moving Block (TD 2.3 / WP4) for different application fields as e.g. urban or main line. These demonstrators are implementing the requirements defined in X2Rail-1 and detailed in X2Rail-3. These laboratory preparations are focusing on various suitable railway applications. Further, processes required for testing of Moving Block approaches shall be investigated in co-funded collaboration with the work package on Zero On-site testing as well as formal modelling for formalizing the specification.

### 2.2.8 Zero On-Site Testing

Apart from the technical development focused key technologies, the topic of "Zero On-Site Testing (ZOST)" (TD 2.6 / WP8 and WP9) is about transferring testing and validating from railway environment into a simulation and testing framework of laboratory testing. In total seven different demonstrators are provided focusing on topics like Moving Block, ATO, ACS, Train Integrity, Smart wayside objects and automatic testing of Traffic Management Systems (TMS) and Passenger Information Systems (PIS). All those tests have been performed on a generic lab test environment architecture based on the results of X23Rail-3.

### 2.2.9 Cyber Security

Cyber Security (TD 2.11 / WP11) concludes the spectrum of key technologies in X2Rail-5. The main focus is on the development of a concept for an Information Sharing and Analysis Center (ISAC). The related work on the Computer Security Incident Response Team (CSIRT) specifically designed for the requirements of the railway operations has been concluded in X2Rail-3 already. Hence the project completes the "Security-by-Design" approach applicable for different railway applications.

### 2.2.10 Technologies supporting migration to ATO over ETCS

In the fourth work package of TAURO further supporting technologies are developed in order to ensure that the migration to ATO over ETCS will become smooth. The specification of the ATO over ETCS is improved by further aspects as the use in non-ETCS areas and the relation to the TMS as well as modelled in a semi-formal way to enable simulations as well as coherency checks.

### 2.2.11 System Integration & Coherence

As the functionalities and technologies of CCS Systems are always highly interdependent, a dedicated work group has been set up where technical experts will come together to ensure technical coordination and system integration within the project. The related transversal work package (WP2) will ensures coherence within all X2Rail projects as well as the liaison with corresponding ERTMS Users Group and UNISIG groups in order to take care that the outputs from the projects will be well prepared to enter smoothly the ERTMS CCM process.

## 2.3 Impact

The Shift2Rail projects TAURO and X2Rail-5 are both supporting the target of rapid and broad deployment of innovations in advanced traffic management as well as command control and signalling systems, by offering improved functionalities and certification procedures, facilitating the migration from today's systems, decreasing overall costs, adapting it to the needs of the different rail segments as well as to the needs of rail becoming an integral part of future multimodal smart mobility system.

### 2.3.12 Enhanced overall reliability, safety and security

The target of higher automation in both projects is focussed on reliable railway operation. Innovations as e.g. the indoor and outdoor perception, automatic status monitoring and diagnostic for autonomous trains as well as the ISAC are focussed to ensure the highest possible availability and reliability and so the service quality for the customers. All innovations are developed in the European Framework and hence applying the current approaches for safety, security and standardisation in Europe.

### 2.3.13 Cost reduction

Making optimal and efficient use of railway system capabilities as well as reducing costs is a major objective of Shit2Rail. Consequently, innovations are developed to increase automation and digitalisation to reduce cost for both – daily operation as well as disturbances. Environment perception and status monitoring will help to identify potential issues early and so reduce cost for maintenance and repair. Procedural innovations as formal modelling for specification and zero on-site testing help to reduce cost in the development and approval process while technological innovations like fail-safe train positioning technologies help to reduce trackside equipment cost.

### 2.3.14 Improved capacity

Automation of rail operation by using e.g. ATO up to GoA4 and moving block contributes to make best use of the capacity of the existing rail infrastructure. The fail-safe real-time train positioning and the improvement of the radio communication to low latencies and sufficiently high bandwidth are technological necessities to ensure optimised automation. Nevertheless, the railway automation is characterised by complex interaction of different systems, which need to be safe but efficient at the same time. In order to show that not only individual innovations have been developed but as well their integration is proven, the ITD in X23Raiö-5 has been done, by showing together moving block, on-board train integrity supervision and adaptable communication with different bearers.

### 2.3.15 Reduction of environmental impact

A major impact of the optimised operation using a well-adjusted combination of Moving Block, ATO over ETCS GoA4 and TMS is a reduction of energy consumption and consequently a reduction of emissions e.g. carbon dioxide or noise (thanks to optimised driving with less acceleration and braking phases) which is an immediate increase in sustainability.

## 2.4 Conclusion

The two projects TAURO and X2Rail-5 are both final projects in the multi-annual Shift2Rail programme. The focus is on development and demonstration in laboratory and field of technologies which are required for digital and automatic train operation. Several different prototypes for those technologies have been implemented and demonstrated in dedicated tests and demos to show the maturity of the solutions as well as the certifiability of these solutions. Environment perception, remote driving and command, automatic status monitoring and diagnostic for autonomous trains as well as further technologies supporting the migration to ATO over ETCS have been provided by TAURO. X2Rail-5 supported by four demonstrations of moving block and several different tests with different telecommunication bearers to demonstrate adaptable communication systems. Fail-safe train positioning was topics of both projects and different tests with stand-alone solution as well as virtual balises have been successfully done. In order to reduce cost for specification and certification formal modelling as well as improved lab-test capabilities have been developed. The latter have been shown on seven demonstrations applied to technologies from other TDs in IP2. Finally, an approach for an Information Sharing and Analysis Center for cyber security has been developed. After the finalisation of both projects, innovations for rail automation and signalling as well as for rail traffic management are the flagship areas FA1 and FA2 in the new Europe’s Rail JU that will take up the results and continue to work on those innovations in the domain of digital, automatic train operation.

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[6] Europe’s Rail Multi-Annual Work Programme (MAWP): https://rail-research.europa.eu/wp-content/uploads/2022/03/EURAIL_MAWP_final.pdf

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## 2.6 Acknowledgements

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Disclaimer: This dissemination of results reflects only the authors' view and the Shift2Rail Joint Undertaking is not responsible for any use that may be made of the information it contains.

## 2.7 Authors

**Javier Goikoetxea,** Dipl.-Ing. joined CAF in 1997 after finishing his studies in mechanical engineering at Tecnun in San Sebastian. Currently he holds the position of Senior Technology Strategist at the Technology Division of CAF. He has been involved in developing advanced technological products for CAF such as the SIBI tilting system, the COSMOS TCMS product or the OARIS high speed train. Javier has a large experience in managing national and international research projects and represents CAF at the ERRAC Steering Committee and UNIFE R&I Committee. Within the Shift2Rail initiative Javier is the Coordinator of the Innovation Programme 1 - Cost-efficient and reliable trains.

E-Mail: jgoikoetxea@caf.net

Dr.-Ing. **Michael Meyer zu Hörste** holds a PHD in mechanical engineering from the technical University of Braunschweig. He has joined DLR Institute of Transportation Systems in 2001 bringing already 6 years of railway research experience with him. He is expert in railway operations, command, control and signalling systems, especially ERTMS/ETCS as well as train localisation. Currently he is working the business development of the DLR Institute of Transportation Systems He was a major contributor in building the DLRs ETCS test laboratory RailSiTe®. He is chairman of the ERTMS Reference Labs Association since 2012. He is fellow of the Institution of Railway Signalling Engineers (FIRSE) since 2012. He is member of the Shift2Rail and EU Rail governing boards as well as the coordinator in the DLR for Shift2Rail and Europe's Rail.

E-Mail: Michael.MeyerzuHoerste@dlr.de

# 3 Regional and Freight demonstrator testing Adaptable Communication System including Channel Characterization Tool

*Nerea Fernández-Berrueta, Jaizki Mendizabal Samper, Iker Moya;*
*CEIT, Donostia / San Sebastián, Guipúzcoa, Spain*

## 3.1 Introduction

GSM-R is an interoperable track-to-radio technology used by many infrastructure managers (IM) and railways undertakings (RU) for operational voice communications. GSM-R also acts as the data bearer for the European Train Control System (ETCS) [1]. However, and focusing on this specific communication technology, GSM-R is obsolete with an end of support planned by 2030 onwards and, it does not accomplish the requirements for the current applications. Some of its limitations are its low link rate [2]: (9.6 kbps/connection), its delay (approx. 400 ms), interferences such as Electromagnetic (EM) transient interferences [3] or public GSM [4], or the small system capacity (19 channels of 0.2MHz bandwidth per channel) [5]. In fact, the needs of the railways are constantly evolving, making GSM-R unable for covering its requirements. Moreover, the telecom standards evolution remains dependent on the telecom industry evolution cycles. Therefore, these considerations led UIC, as soon as 2012, to launch the first studies for a successor to GSM-R [6].

**FRMCS and ACS**

As already stated, it is inevitably necessary to switch to a technology that allows a higher performance in transmission [1]. According to [7], the following radio technologies are considered the most likely technology candidates for future railway communication:  4G (LTE-A), 5G, and SATCOM (L-Band, S-Band). Therefore, an evolution of the current communication technology is needed.

To start with, Future Railway Mobile Communication System (FRMCS) is a project initiated by the International Union of Railways (UIC) to develop a new global standard for railway communication systems, in close cooperation with the different stakeholders from the rail sector, as the successor of GSM-R but also as a key enabler for rail transport digitalisation [6]. The main objective of FRMCS is to provide a unified and interoperable communication system for the railway sector, to support the growth of rail traffic, and improve its efficiency. Moreover, Adaptable Communication System (ACS) Shift2Rail is a communication system developed jointly by industry and railway operators as a possible successor covering all types of railways and all aspects of the FRMCS [8]. The aim of ACS Shift2Rail is to provide a more flexible, reliable, and efficient communication infrastructure for the railway sector. Within S2R the ACS was specified to test technical concepts which can be used in the FRMCS.

The abstract focuses on the ACS perspective: Section 2 describes the target scenario for this abstract in a more detailed manner being the regional and freight demonstrator and its selected technologies. Then, Section 3 presents the Channel Characterization Tool (CCT) application, one of the applications that are connected to the demonstrator. Furthermore, Section 4 shows the corresponding integration between the demonstrator and the application. Afterward, Section 5 shows some preliminary results to later on, describe the future work to be done in Section 6. Finally, Section 7 states some conclusions.

## 3.2 Scenarios and Technologies in ACS

Figure 3-1 shows the generic ACS system architecture for the three different demonstrators (mainline, regional and freight, urban) selected [11]. The ACS consists of two different parts: on-board (on the bottom) and trackside (on the top). The ground-side central application domain consists of data storage and applications. Then, they communicate with the ACS unit via a central network and sequentially, with the onboard ACS unit using whichever bearer is selected. The on-board ACS then communicates with the on-board applications by means of the train network. The exact architectural details and implementation vary among the demonstrators such that a variety of wireless technologies, network architectures, and railway applications are trialled [11].

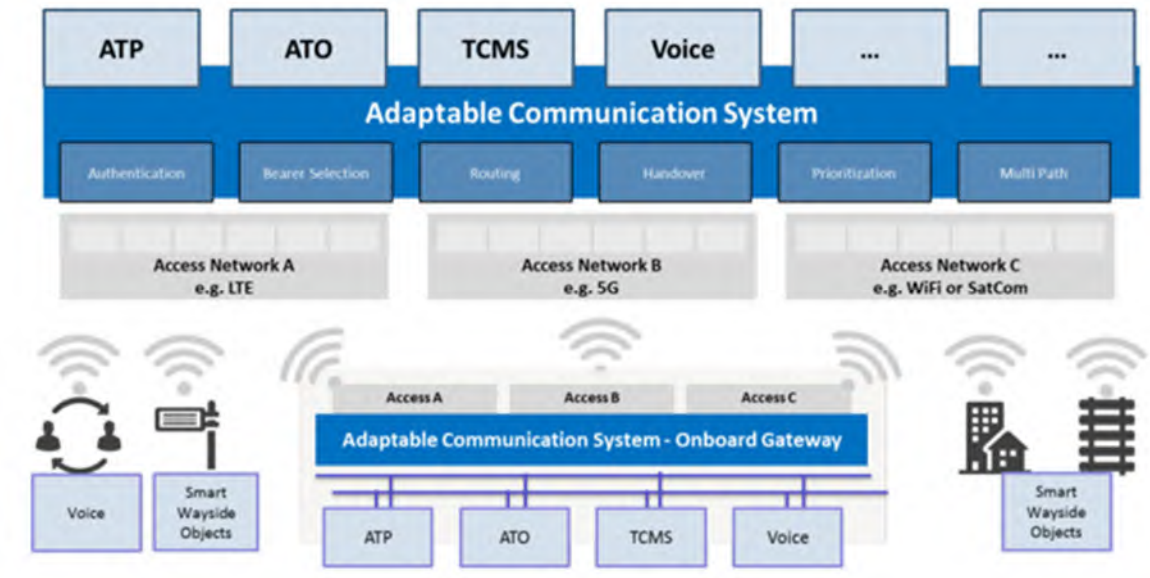



Figure 3-1: ACS system architecture

The ACS can manage both terrestrial and satellite bearers, taking advantage of its technology-independent architecture. Particularly, the target ACS in this abstract uses heterogeneous public networks such as the available Public Land Mobile Networks (PLMNs) from different operators & Satellite Communication (SatCom).

## 3.3 CCT prototype

The ACS is the system in charge of managing the different available bearers to connect the on-board and the trackside. At the same time, different applications connect to it with different purposes (critical applications, Internet of passengers, etc.). One of these applications is the CCT. The CCT is capable of measuring the performance of the available communication technologies geolocating each parameter at a specific point on the track. In this way, how communication technology behaves in different environments can be known as [12] explains more in detail.

In the context of a regional/freight demonstrator, the CCT application will be exploited to validate the capabilities of the ACS gateway which deals with traffic having different QoS levels.

The CCT consists of two different parts, in order to perform the required measurements:

- On-board:
  - CCT Agent: it is the equipment installed on-board connected to the on-board ACS gateway. It receives the information for the configuration of testing, performs the corresponding tests, and sends the results to the CCT Server.
- Trackside:
  - CCT Server: it is located on the trackside, more specifically in Hitachi Rail STS premises (Italy). It communicates with the CCT Agent and CCT CI, testing the performance of the available communication technologies managed by the ACS gateway and receiving the configuration, respectively.
  - CCT CI (Control Interface): on the one hand, it allows to configure the tests to be executed by the user, and on the other hand, it offers the visualization of the test results, shown in different formats such as maps or graphics:
    - Configuration of each of the CCT_Agent to activate/deactivate them to monitor the parameters defined in the time interval that the user wants.
    - Visualization: the user can visualize the results in different display modes:
      - Maps: the web interface shows in a map the different values along the track where the train was passing through during the test.
      - Graphics/charts: the CI shows charts comparing time vs. value.
    - Key System Requirements (KSR) chart: the quality of service of each application to work properly in chart form. In this way, this chart can be compared with the other charts from the test, letting the user know which applications will work or not (comparison with one impairment).

**On-board equipment: CCT Agent**

The CCT Agent receives the information for the configuration of testing, performs the corresponding tests, and sends the results to the CCT Server. Different modes of configuration for the CCT are available depending on the communication technologies to be tested or the integration with other systems such as ACS. The regular on-board hardware for normal functioning is shown in Figure 3-2. Nevertheless, due to the integration with the regional/freight demonstrator, some of the outputs (such as SMAs connections) can be replaced by Ethernet connections, when needed.


Figure 3-2: CCT Agent up to LTE


Figure 3-3: CCT Agent up to 5G

Starting with an equipment up to LTE, CCT has evolved and adapted to new generations of communication technologies such as 5G as Figure 3-3 shows. Consequently, an adaptation of the CCT stated in [12] has been implemented for measuring the performance of 5G technology which can be Non-Stand Alone (NSA) and Stand Alone (SA) which CCT can measure.

Then, the CCT is completely adapted in a standalone functioning to measure the different capabilities of the communication technology.

**Trackside equipment: CCT Server and CCT Control Interface**

The CCT Server is responsible to send to the CCT_Agent the test to be performed, executing this test, and send the results. It can be allocated in a virtual machine.

The CCT CI allows the configuration for performance testing and visualization. Therefore, the results from the configured test campaign can be shown in the CCT CI. As an example, the results obtained from the use of CCT, during a specific test campaign to measure the performance of 5G technology, rise some conclusions from the obtained results such as:

- Partial coverage of the given route corresponding to the test campaign for 5G.
- Data rates are higher than the ones from 4G (approx. 500 Mbps for downlink and 100 Mbps for uplink).
- Round Trip Time (RTT) values are lower than the ones for 4G.

Some examples of how the CCT CI represents the results are shown below, being the results exposed via maps, charts, or histograms from the same test.

As already mentioned, in this specific test, the CCT measured the performance of the available technology in San Sebastián, being up to 5G. Regarding the results on the map, Figure 3-4 shows both, the values of the measured parameter, in this case, bandwidth, during the route, reaching values close to 400 Mbps, and the technologies available at each point, being NR 5G-NSA at almost every point and LTE at few ones. Then, thank to these figures, the performance of the communication technology can be known at each point of the route. In this case, it allows knowing that there is a critical point where a vertical handover happens from 5G to 4G due to lack of coverage. As a consequence, the performance lowers as the figure on the left shows. Apart from the coverage, other factors can affect the desired signal such as obstacles. Thanks to the CCT, the reduction in performance due to external factors can be found at the exact point allowing the user to look for the reasons affecting the communication technology.

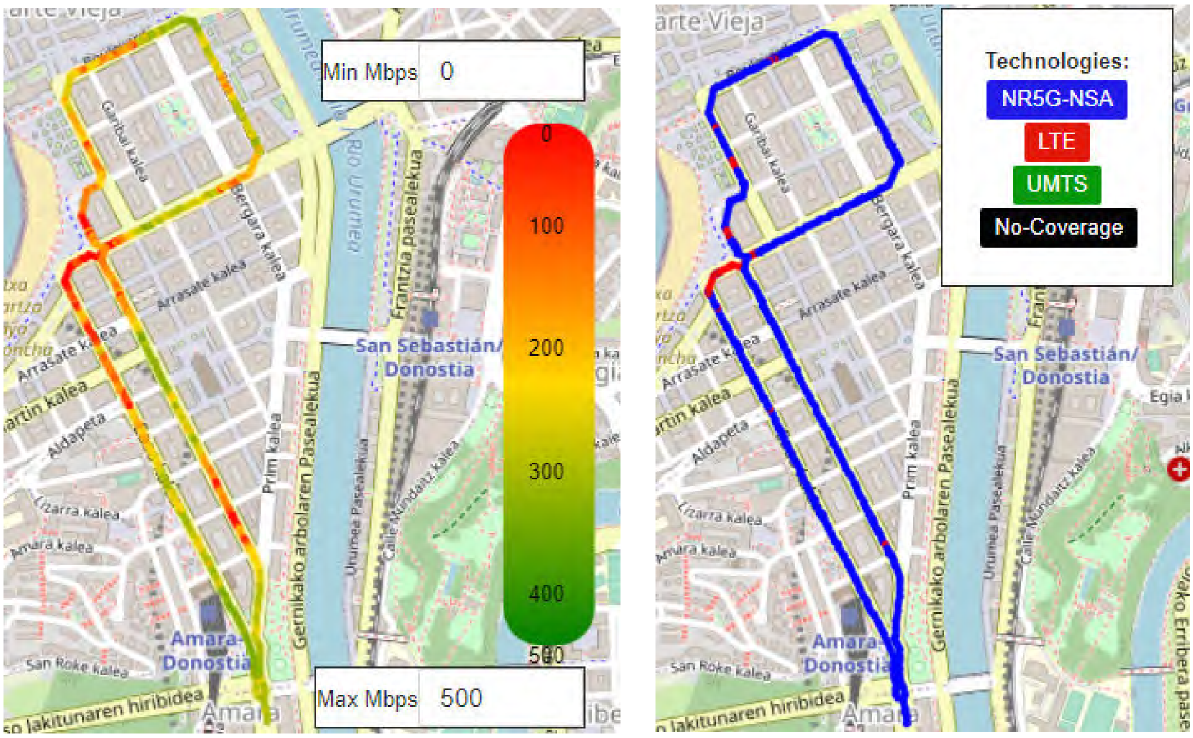



Figure 3-4: Results on the map

Figure 3-5 and Figure 3-6 represent the values above shown on the maps through timeline graphics. Then, Figure 3-5 shows the bandwidth values measured over time along the route for the test while Figure 3-6 shows the RF values measured over time along the route for the test. Moreover, the tool provides different parameters such as the average, minimum, and maximum values of the measured parameter. In this way, the information is exposed differently, letting the user know, e.g., if the quality of the signal for the target technology has been reduced and consequently affecting its performance. For example, Figure 3-6 shows from 9:44 to 9:46 the best values for RF which match with the information exposed in Figure 3-5 (the best performance in terms of data rate).

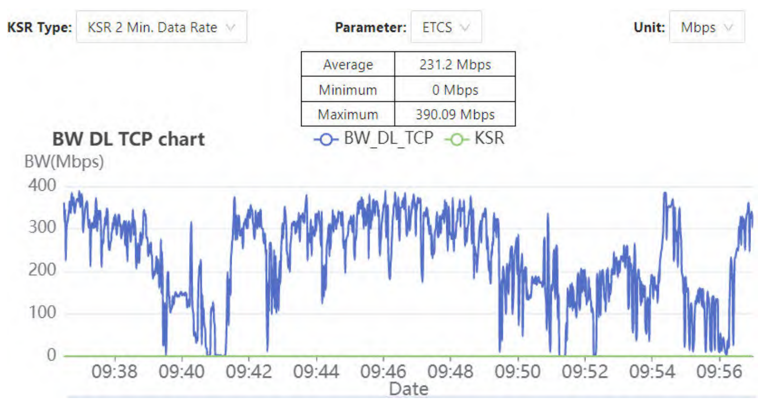
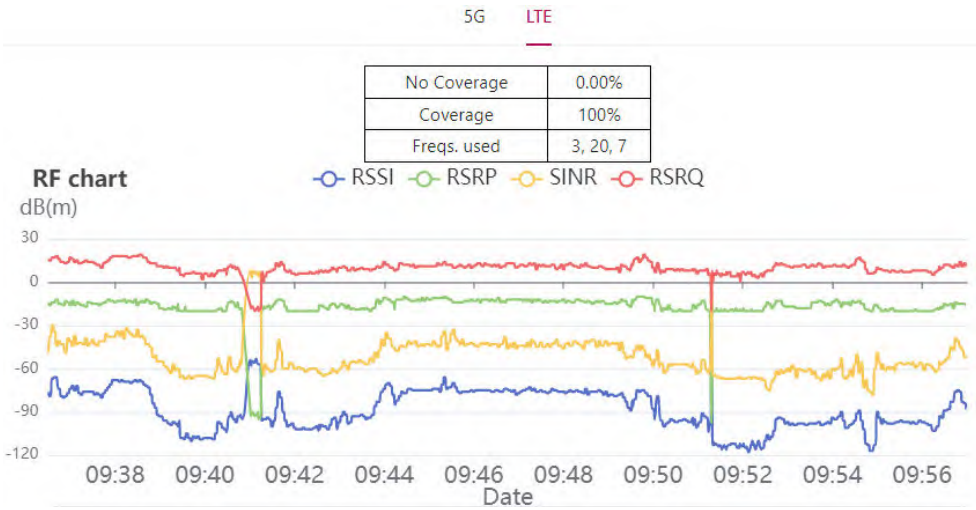



Figure 3-5: Time vs Bandwidth values

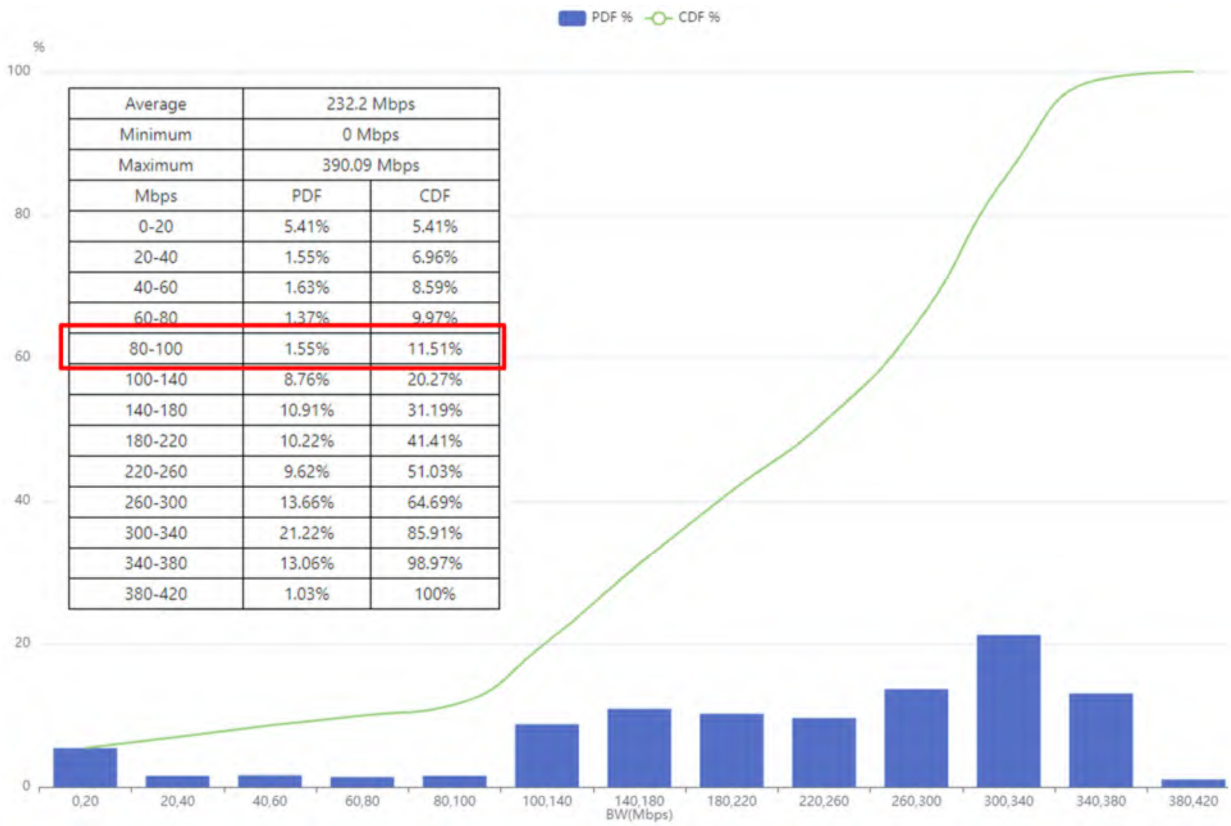


| | |
|---|---|
| No Coverage | 0.00% |
| Coverage | 100% |
| Freqs. used | 3, 20, 7 |



Figure 3-6: RF values vs time

Not only the CCT shows the information in maps and timeline charts but also histogram format is available. Figure 3-7 shows the Probability Density Function (PDF) and Cumulative Distribution Function (CDF) in chart form and table. In this way, it can be known some interesting aspects of the technology such as the percentage of values below a threshold, in this case, 11.51% of the values are below 100 Mbps.



| | | |
|---|---|---|
| Average | 232.2 Mbps | |
| Minimum | 0 Mbps | |
| Maximum | 390.09 Mbps | |
| Mbps | PDF | CDF |
| 0-20 | 5.41% | 5.41% |
| 20-40 | 1.55% | 6.96% |
| 40-60 | 1.63% | 8.59% |
| 60-80 | 1.37% | 9.97% |
| 80-100 | 1.55% | 11.51% |
| 100-140 | 8.76% | 20.27% |
| 140-180 | 10.91% | 31.19% |
| 180-220 | 10.22% | 41.41% |
| 220-260 | 9.62% | 51.03% |
| 260-300 | 13.66% | 64.69% |
| 300-340 | 21.22% | 85.91% |
| 340-380 | 13.06% | 98.97% |
| 380-420 | 1.03% | 100% |



Figure 3-7: Histogram for the Bandwidth values

## 3.4 Demonstrator and prototype

After explaining the target prototype, that is to say, the CCT, the integration with its corresponding demonstrator is needed. The regional and freight demonstrator is designed and implemented by Hitachi Rail STS to be used in the regional and freight operations. This demonstrator contains the ACS that consists of an on-board part and another one on the trackside. The ACS manages different applications such as ETCS or the CCT application, which this paper focuses on. Figure 3-8 shows the general architecture for the regional and freight demonstrator.

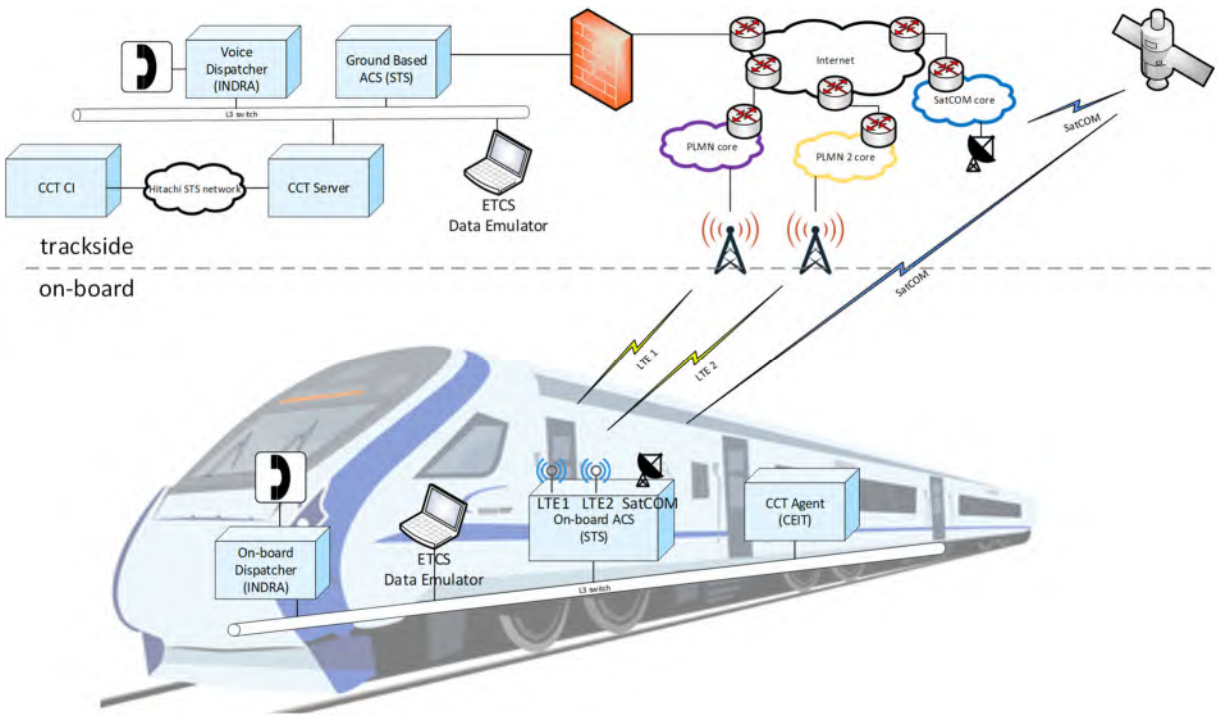



Figure 3-8: General architecture for the regional and freight demonstrator

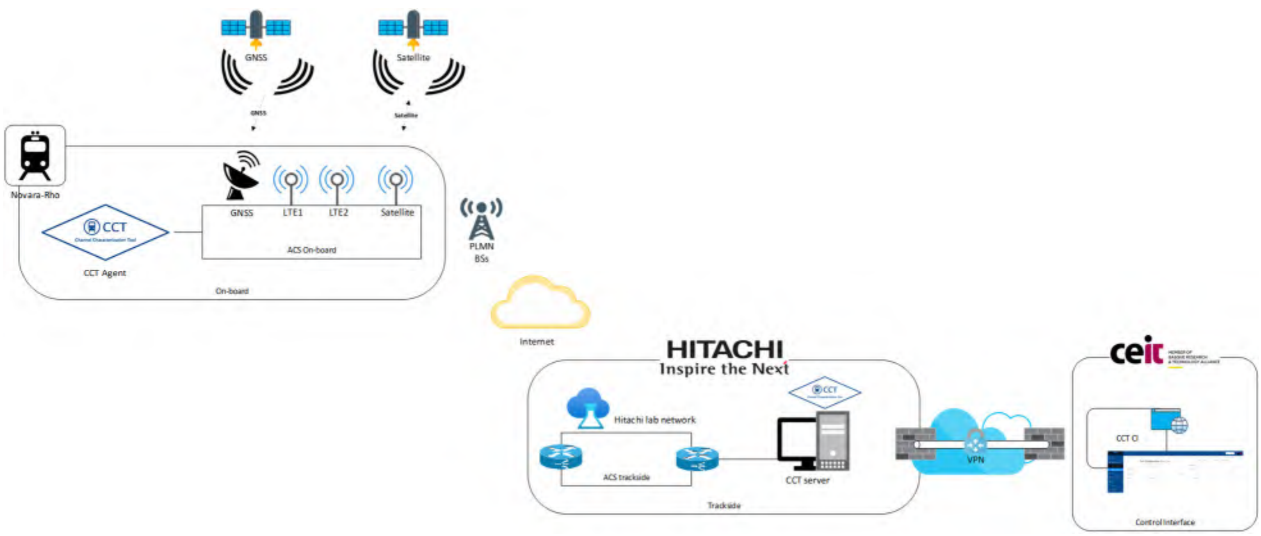



Figure 3-9: Onsite testing schema

For the field tests, CEIT's CCT and Hitachi's ACS need to be integrated. The CCT Agent is supposed to be installed on-board connected to the ACS, the CCT Server is located in Hitachi Rail STS premises, being allocated in a virtual machine and the CCT CI is located in CEIT premises. Then, Figure 3-9 shows the schema for the integration testing including the ACS and the CCT.

Respecting the CCT Agent, it required an adaptation for the integration compared to the CCT Agent explained in Section 3: some of the outputs (such as SMAs connections) have been replaced by an Ethernet connection. Moreover, some information such as the position or the RF values is currently provided by the ACS on-board via Ethernet instead of GNSS receiver or RF (SMA) as it does in standalone mode. After the required adaptation, the CCT was successfully integrated with the demonstrator.

Then, the CCT is capable of measuring the performance of the available communication technologies managed by the ACS, geo-localizing them in order to map the result along the entire test track. In this context, the CCT application will be exploited to validate the capabilities of the ACS gateway which deals with traffic having different QoS levels.

The test to be configured in the test campaign are:

- RTT
- Throughput downlink TCP
- Throughput uplink TCP
- Throughput downlink UDP
- Throughput uplink UDP

The bandwidth test that CCT can normally perform, is not possible in this demonstrator as there is a limit in the data usage.

However, as the on-site testing was not available for the expected dates, some static tests were performed in order to test the ACS. Then, some modifications respecting the schema have been done for this purpose. These static tests were performed by connecting both networks through a VPN connection, having the CCT CI and the CCT Agent in CEIT premises and the rest of the architecture in Hitachi Rail STS as Figure 3-10 shows.

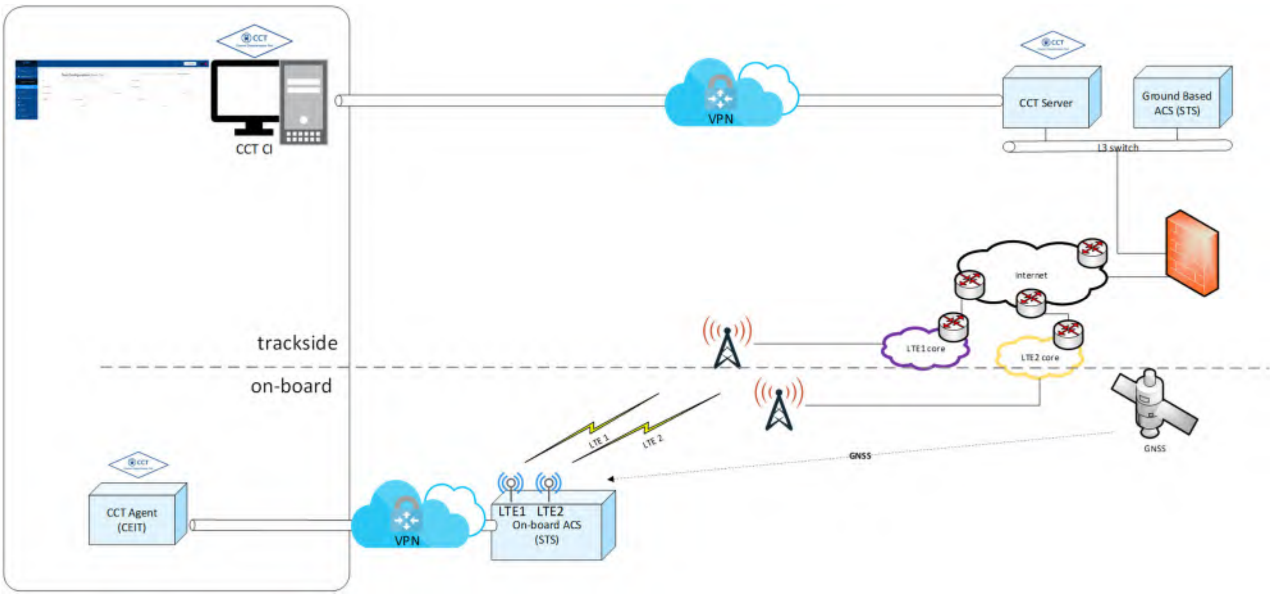



Figure 3-10: Integration and static test setup

## 3.5 Preliminary results from the static tests

The static tests have been carried out with the equipment corresponding to the ACS from Hitachi Rail STS and the CCT Application from CEIT. The whole system was split into two locations being connected by a remote VPN. While the ACS both, on-board and trackside, and the CCT Server were located in Hitachi Rail STS premises, the CCT Agent and CCT CI were located in CEIT.

The differences with the on-site testing are:

- The CCT on-board is placed in CEIT. Then, the latencies measured in the static test are not only the measurements corresponding to the wireless technologies but also the latency because of the VPN connections added to it.
- The position of the CCT Agent is placed at a static point as it is given by the ACS on-board placed in Hitachi Rail STS while, from the on-site testing, a route should be shown.
- The measured values are similar as the technology remains stable.
- There is no contemplation of handovers as the on-board is not in movement.

The test configured in the static tests are:

- RTT
- Throughput downlink TCP
- Throughput uplink TCP
- Throughput downlink UDP

- Throughput uplink UDP

After sending the configuration test and executing it, the results are available to be shown in the visualization part of the CCT CI. As explained, the maps and charts can be found in the visualization part.

Firstly, the map pointing out the location and technology of the on-board being used by the CCT is shown in Figure 3-11. As the tests were static ones, the result is a point in the same location (Hitachi Rail STS premises in Genoa), as it is given by the ACS on-board placed in Genoa, being the current technology LTE.


Figure 3-11: RF values on the map

All the results obtained from configuring these tests are compared within charts and the KSR defined in [10]. In this case, and as ETCS is another application in the regional and freight demonstrator, the KSR compared with the obtained results in each case is the defined value corresponding to the ETCS application.

The first performed test is the measurement of the RTT. As there are different technologies present in the demonstrator (LTE from different network operators) in order to transmit the information between the trackside and the on-board, both are measured at the same time.

**KSR Type:** KSR 1 Max. Latency

**Parameter:** ETCS

| LTE1 | |
|---|---|
| Average | 118.52 ms |
| Minimum | 100.55 ms |
| Maximum | 188.5 ms |

| LTE2 | |
|---|---|
| Average | 117.57 ms |
| Minimum | 104.33 ms |
| Maximum | 828.47 ms |

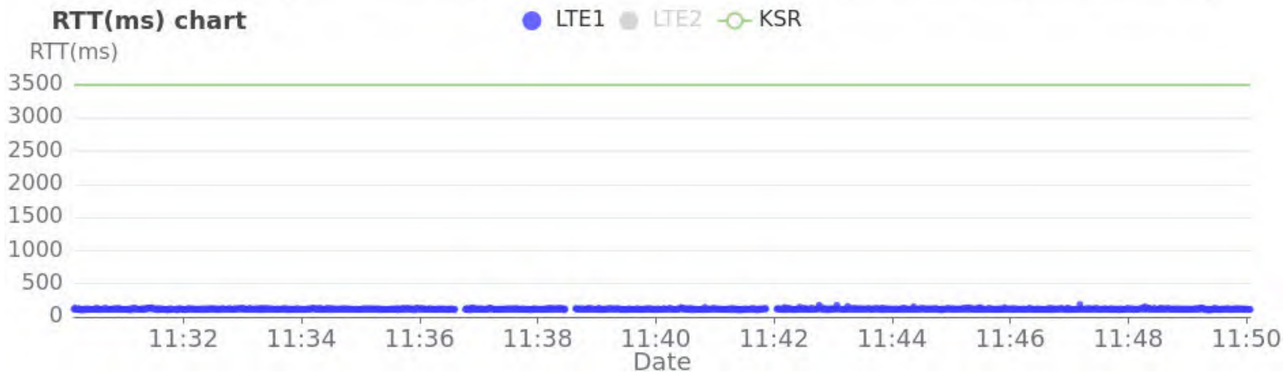



Figure 3-12: Measurement for the RTT parameter with LTE1


Figure 3-13: Measurement for the RTT parameter with LTE2

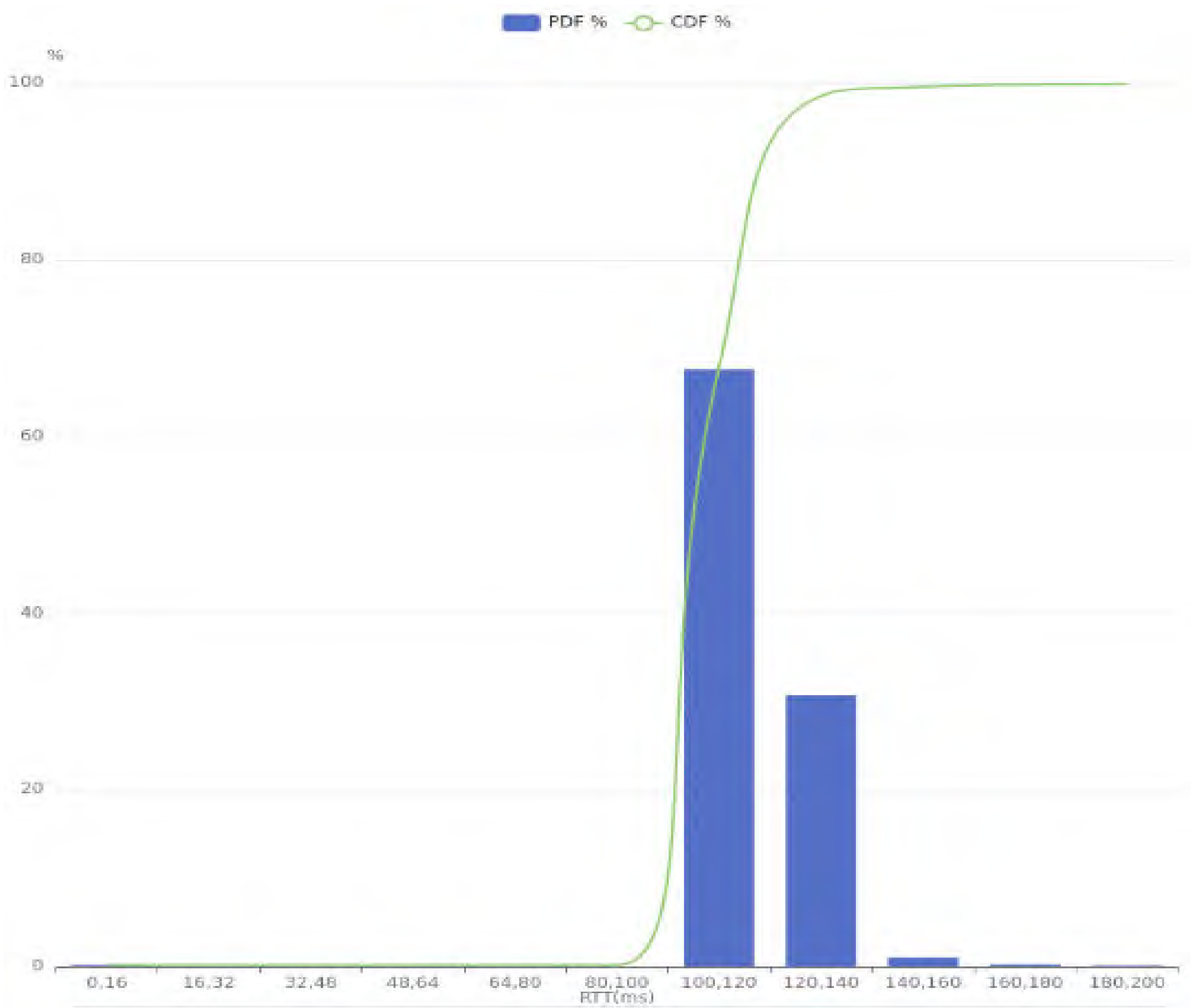



Figure 3-14: Histogram for LTE1


Figure 3-15: Histogram for LTE2

It can be seen as both technologies have approximately the same features for RTT; the majority of the values from both technologies are in the range between 100 and 120 ms as Figure 3-12, Figure 3-13, Figure 3-14, and Figure 3-15 show.

Moreover, in these tests, the RF values are always the same, being stable values, as the test is static. Nevertheless, depending on the network operator, the RF values change as they do not have the same point as the base station or emitting with the same power. Figure 3-16 and Figure 3-17 show the RF-measured values.

| | |
|---|---|
| No Coverage | 0% |
| Coverage | 100% |
| Freqs. used | LTE->0 |

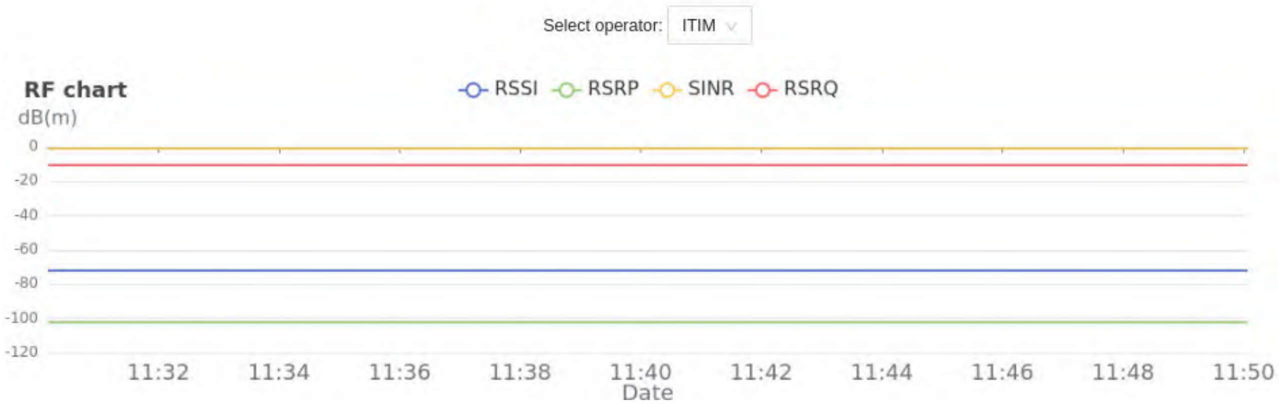



Figure 3-16: RF value for ITIM network operator

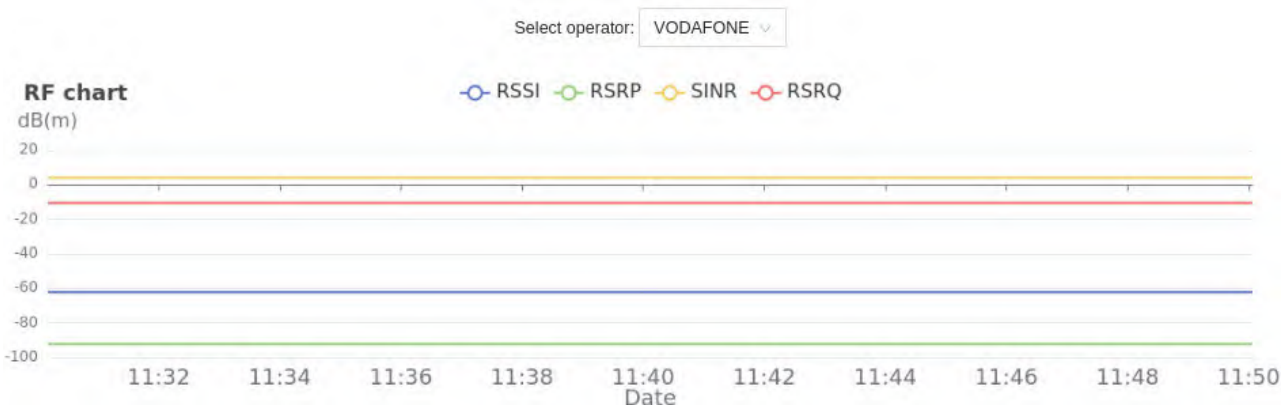



Figure 3-17: RF values for Vodafone network operator

In both cases, the coverage was measured as 100% of LTE technology without vertical handovers to another technology. In this case, the full coverage is not a relevant parameter as the tests were performed in static conditions.

Regarding the configured throughput belonging to some applications, the ACS showed that is capable of managing these data rates. Remarkably, the packet loss corresponds to 0. Figure 3-18 and Figure 3-19 show the result of the data rate corresponding to TCP traffic. In the static, UDP traffic is also generated giving the same result as the TCP one.

KSR Type: KSR data rate TP DL min data rate for thoughput dl tcp    Parameter: ETCS    Unit: Kbps

| | |
|---|---|
| Average | 412.79 Kbps |
| Minimum | 371.04 Kbps |
| Maximum | 442.64 Kbps |

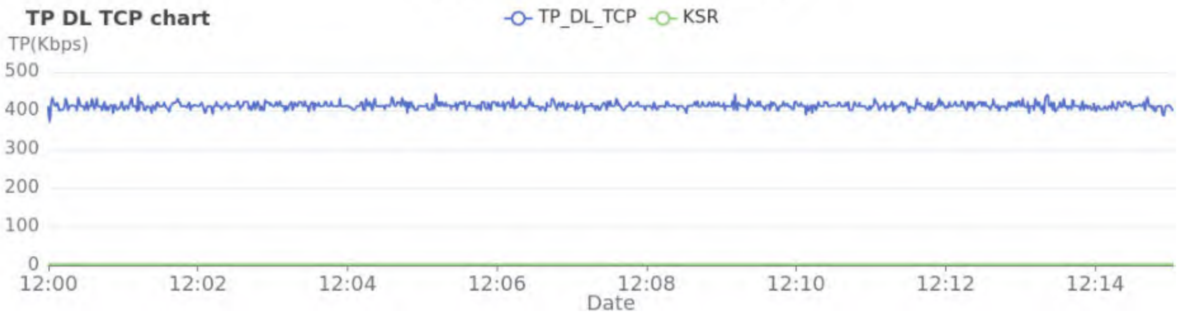



Figure 3-18: Throughput DL TCP

| | |
|---|---|
| Average | 390.9 Kbps |
| Minimum | 225.12 Kbps |
| Maximum | 552.16 Kbps |

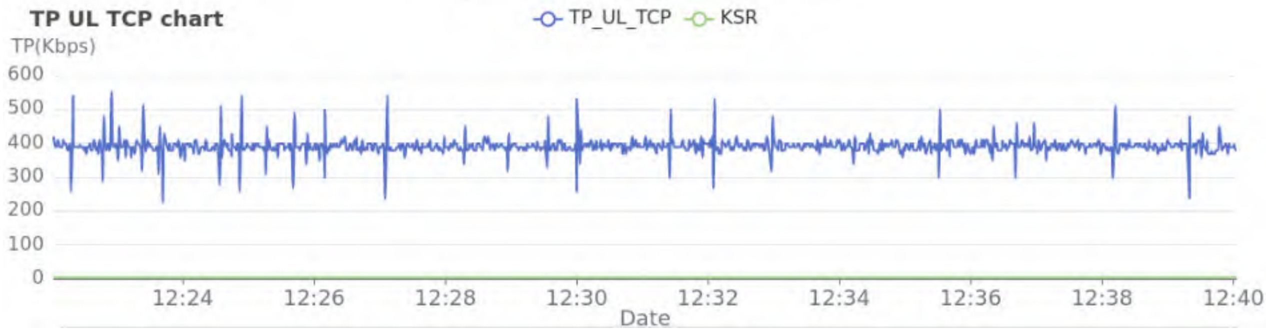



Figure 3-19: Throughput UL TCP

These results are obtained from the static tests then, in general, the values of the measured parameters remain stable. When the on-site testing will be performed, these measured parameters will vary due to external factors affecting the target technology such as obstacles or coverage. For example, in the case of the throughput, a drastic reduction in the Quality of Service of the communication bearer, which will be shown in RF charts, could imply an increase in packet loss.

## 3.6 Future works

The ACS and the CCT integrated into the demonstrator are expected to be tested on-site. The selected track for the on-site testing will be the track between Novara and Rho Lombardy, Italy, which has a total length of 35,64 km, as Figure 3-20 shows.

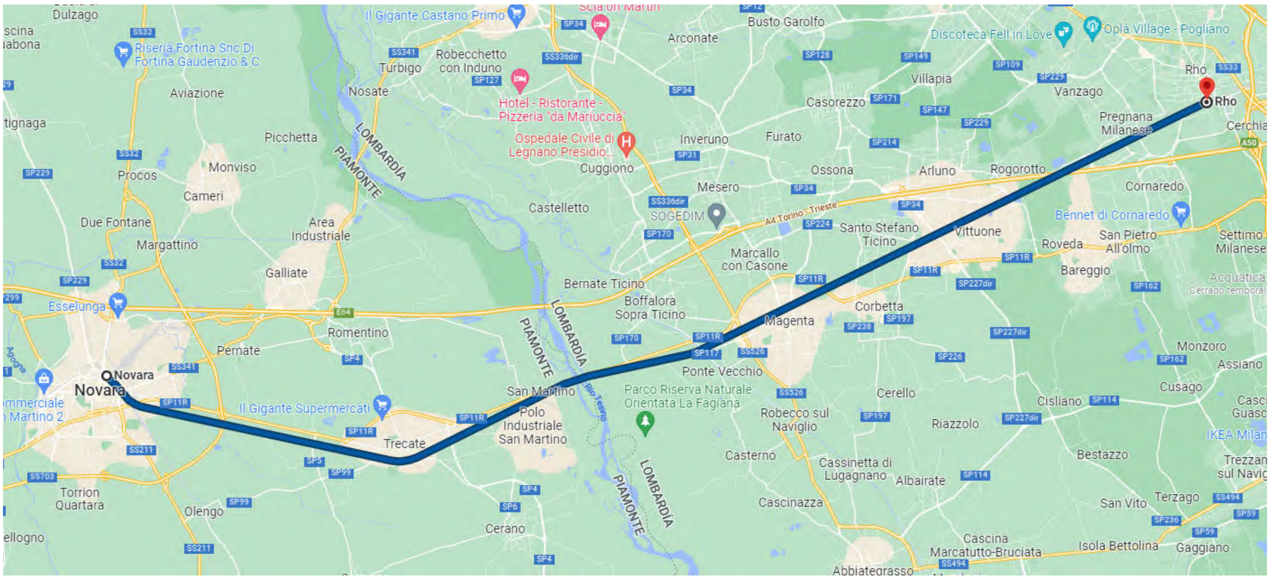



Figure 3-20: Track for on-site testing Novara-Rho

This test campaign is expected to take some days in order to measure the different parameters that the CCT is capable of doing. In this way, the ACS will be tested and the different parameters selected for the measurements will determine how the whole communication behaves.

After the on-site testing and thanks to the CCT, the parameters of the performance of the communication technologies along the track will rise some interesting results determining the capabilities of both, ACS and the current technologies being used during the test. In this way, the behaviour of the technologies will be found out knowing how a given application such as ETCS would behave. As well, the capabilities of the ACS will be tested as is the system managing the communication technologies between the on-board and trackside.

## 3.7 Conclusions

The ACS tests some technical concepts for the evolution of the GSM-R as it has to be replaced. Therefore, different demonstrators have been developed within this idea. Moreover, as each demonstrator has different characteristics, i.e. the environment (tunnels, open space, etc.), different technologies were selected. In the case of the regional and freight demonstrator, LTE technology from different network operators is tested. After some preliminary tests in static mode, it can be stated that the integration was successfully completed and both, the ACS and the LTE technologies are working. Moreover, and comparing the results to the KSRs for the ETCS application, it would seem that this application would work in the whole track under the same conditions already measured. However, dynamic on-site testing could rise different results compared with static testing due to the different environments affecting the target technology along the track or the lack of coverage at some places on the track.

In this case, thanks to the CCT in the setup of the regional and freight demonstrator, some relevant information can be obtained via its results from performing the tests:

- The ACS behaviour respecting the applications connected to it.

- How the performance of the technologies is along the track.
- The coverage on a map along the track.
- The quality of the signal on a map along the track.

In this way, it can be found if the ACS is behaving correctly and whether the technologies along the track are providing enough quality for the requirements of the applications or not.

Then, in order to have the final conclusions for the regional and freight demonstrator, on-site testing should be carried out.

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European Union Funding
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## 3.10 Authors

**Nerea Fernández-Berrueta** received the M.Sc. degree in tele-communications engineering from the Faculty of Engineering, University of the Basque Country, Bilbao, in 2016 and the Ph.D. degree from TECNUN (University of Navarra, San Sebastián, Spain) in 2022. She joined the CEIT-BRTA Research Centre, San Sebastián, in 2017. Her research activity lies in the field of railway signalling, especially in zero on-site testing and adaptable communication systems in the Transport and Sustainable Mobility group. She is now actively participating in H2020 European funded, such as Shift2Rail projects in railway communications and testing: X2Rail-5, and in projects related to 5G technology such as 5G Euskadi.

e-mail: nfernandez@ceit.es

**Jaizki Mendizabal** received his M.Sc. and Ph.D. degrees in Electrical Engineering from TECNUN (University of Navarra, San Sebastián, Spain) in 2000 and 2006 respectively. He joined Fraunhofer Institute (Germany) and SANYO Electric Ltd, Japan as RF-IC designer. Nowadays, he is at CEIT-BRTA, in San Sebastián (Spain) where his research interests include communications and electronic systems. He is lecturing "Communications Electronics" and "Communications via Radio" at TECNUN (University of Navarra).

e-mail: jmendizabal@ceit.es

**Iker Moya** received his M.Sc. degree in Computational Engineering and Intelligent Systems from the University of the Basque Country UPV-EHU, obtained in 2017 and 2019, respectively. Since 2017, he has been working at the CEIT Research Centre in San Sebastian, where he has developed his research career in the sustainable transport and mobility group, belonging to the transport and energy division. In his professional activity, he has focused on software development in various programming languages such as C/C++, Java, and Python. He has specialized in designing and administering embedded systems, gaining experience in implementing positioning and auscultation algorithms for railway infrastructures. Moreover, he has acquired expertise in wireless network quality and machine learning algorithm implementation.

e-mail: imoya@ceit.es

# 4 Satellite Communication for the Adaptable Railway Communication System, Lab-Test Results and Field Test Preparation

*Benjamin Barth, Marcel Grec, Stefan Erl, Norma Montealegre, Alessandro de Rienzo; DLR, Institute of Communication and Navigation, Oberpfaffenhofen, Wessling, Germany*

## 4.1 Introduction

This paper reports the activities of the X2Rail-5 WP3 work done on an adaptable communication system (ACS) in relation to satellite communication (SatCom). As illustrated in Figure 4-1, the ACS connects trackside applications with on-board side. Since coverage along the lines with a dedicated system (railway operator owned) is expensive, it can be supplemented using available public networks or other technologies. The ACS can use several access networks such as 5G, LTE, SatCom, WIFI etc. so-called bearers. Thereby, the ACS provides connectivity via the bearers in a transparent way to the applications by providing session control functions, such as authentication, bearer selection, Quality of Service (QoS) control etc., and the necessary interfaces towards the bearers. Applications register at the ACS with a set of QoS parameters and the ACS aims to meet these by selecting a proper bearer and change it if network conditions require to. The ACS is by definition bearer agnostic and could be enhanced to any kind of bearer.

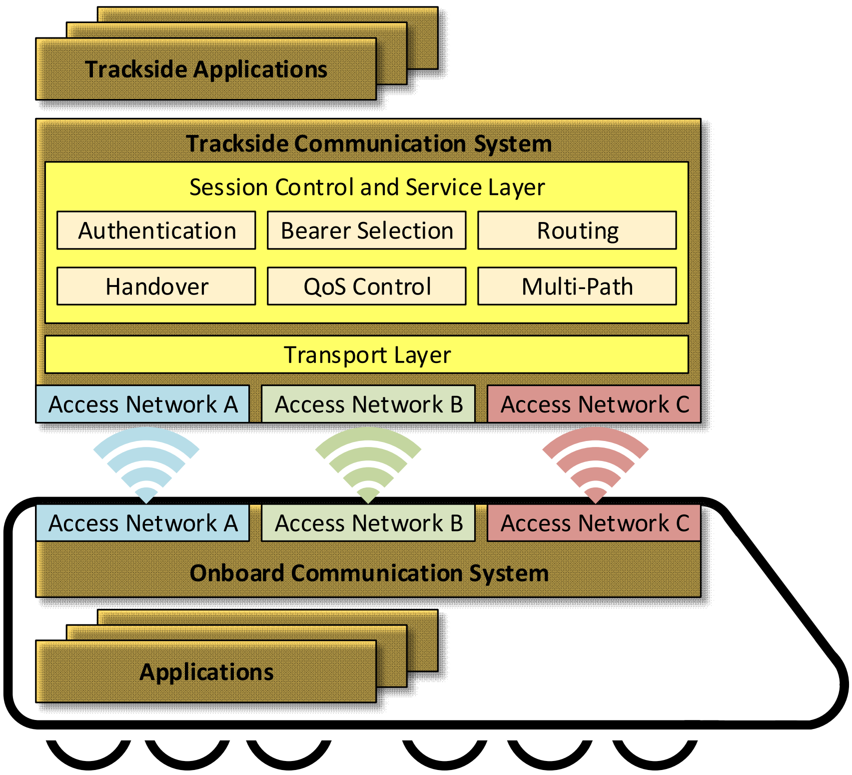


Figure 4-1: ACS general architecture

This approach decouples the application layer from transport as required by the Future Mobile Railway Communication System (FRMCS) user requirements [1]. The FRMCS is currently standardized as a successor to the GSM-R technology which will be obsolete in 2030.

During the project, three ACS demonstrators have been implemented by different companies each for different scenarios (Urban/Suburban, Mainline Highspeed, Regional and Freight) and tested in lab and in field.

In this context, considerations for SatCom as a bearer have been introduced in [2]. Accordingly, SatComs have the main advantage of covering large areas with low capital expenditure compared to the terrestrial infrastructure which makes it interesting for several use cases in the railway domain (by comparing SatCom capabilities and railway communication use cases from [3]):

- IoT connectivity, e.g. to connect smart way-side objects.
- Video connectivity such as for monitoring stations in remote areas and connecting cameras to a centralized control center.
- Virtual balises for assisting next generation signaling schemes
- Passenger communications, in combination with terrestrial technologies, especially in rural areas [4].
- A fallback solution for when terrestrial infrastructure is damaged.
- Reducing track side vandalism since there is a reduction in infrastructure [5].
- A compliment to terrestrial communication systems and act as a backup in case of missing coverage or during hand-over procedures.

In order to investigate if current SatComs can be used for FRMCS, a study was initiated by the European Union Agency for Railways (ERA) which revealed that none of the systems can fulfill all requirements [6]. It also stated the disadvantages that SatCom has for serving railways, which are: operational expenditure; availability; use of dedicated handheld devices; latency due to the round-trip time of the signal in case of Geostationary Earth Orbit (GEO) and Medium Earth Orbit (MEO) systems, which especially impacts voice communications. The SatCom systems analyzed in the study differ in setup and technologies used such that each system has specific characteristics that cannot be generalized. The best solution found was a theoretical MEO system (C-band, constellation of 10-15 satellites) which only lacked a suitable security mechanism in order to fulfill the requirements. All this implies that either SatCom systems can only be used for applications with less strict requirements, or consideration should be given to relaxing the requirements if circumstances allow, e.g. in less congested conditions on the track in regional scenarios.

In line with this, in another study funded by ESA [7], it was found that additionally in a GEO solution the capacity requirements are demanding especially considering autonomous driving and video transmission and need further investigations. A LEO constellation would be able to fully achieve all requirements. Given this, we decided to focus with our developments on signaling (i.e. ETCS) since here SatCom can fulfill the requirements.

In order to demonstrate the applicability of SatComs to the railway sector and perform investigations in a lab, a prototype based on Software Defined Radio (SDR) has been implemented which offers flexibility and may be adapted to many different telecommunication systems [8]. In order to demonstrate its applicability to the railway sector, we are integrating this SatCom prototype as bearer for the ACS in lab.

The prototype could in principle be used for every scenario of the project. However, especially for the urban area, it is expected that the requirements can be addressed entirely by terrestrial technologies since they are highly available and the coverage of SatCom suffers due to shadowing caused by buildings [6]. The biggest advantage of SatCom is the coverage area which can save a lot of costs, especially in rural areas where additional terrestrial infrastructure would be needed. Hence, SatCom is considered for the regional/freight line and for the mainline/highspeed line demonstrators, also during the field test. In the following we (I) present some details of the ACS as background; (II) given a brief overview of the SatCom prototype lab setup and results; (III) Illustrate the field test setup which used a commercial SatCom system.

## 4.2 The Adaptable Communication System

Figure 4-2 present the ACS Layers connecting the application domain with the Network Domain [9]. The ACS layer consists of the ACS control Plane, the ACS Tunnel Management and the ACS user plane which provides connectivity via an ACS Onboard Gateway to an ACS Network Gateway.

The Application Domain interfaces via an ACS Client. The Network Domain performs the transport layer communication via one or more transport network(s), such as SatCom. The connection of the Network Domain/Transport Layer is established by IP service connections.

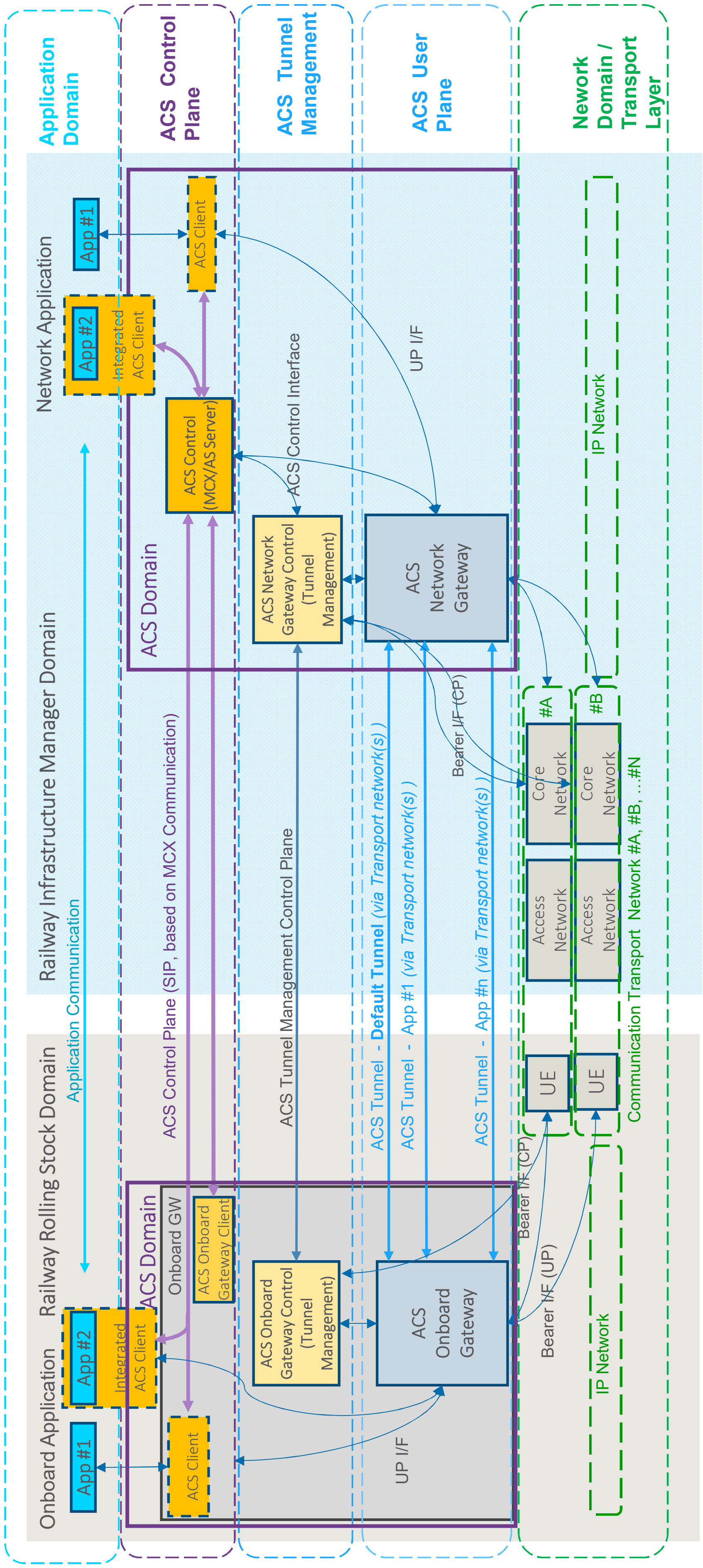


Figure 4-2: The ACS Layers [9]

The ACS provides a common application interface for any interaction between the ACS itself and the railway applications. The following functional scope is provided for applications using the ACS in order to provide a transparent connection:

- Registration
- Identification
- Authentication
- Authorization
- Session Management
- Session setup
- Addressing
- Communication characteristics (QoS)
- Session negotiation
- Session termination
- Service management:
- Location
- Communication characteristics
- Coverage (hotspots geolocation information)

The applications request towards the ACS Control Plane their requirements for communication needs – both on onboard-side and network-side. The ACS Control Plane then controls and grants the communication via the ACS Tunnel Management and ACS User Plane by providing an interface for applications domain for: Identity Management; Addressing; Session Management and Service Management. The ACS Tunnel Management acts as subcomponent of the control plane to steer the network domain functions for the Session Management. Note that MCX has been selected as ACS Control plane (also in line with FRMCS), but in principle also other options can be used. The ACS User Plane then performs the bearer selection (incl. default bearer); routing, handover, multipath (redundancy/ aggregation), QoS control and security.

## 4.3 SatCom Prototype

We develop a SatCom Prototype based on SDR which has been introduced in [8]. The prototype consists of a gateway side which is connected to the track-side of the ACS and a user terminal connecting the onboard-side as illustrated in Figure 4-3. User terminal and gateway are connected by a satellite return link (from user to gateway via satellite), and forward link (from gateway via satellite to user).

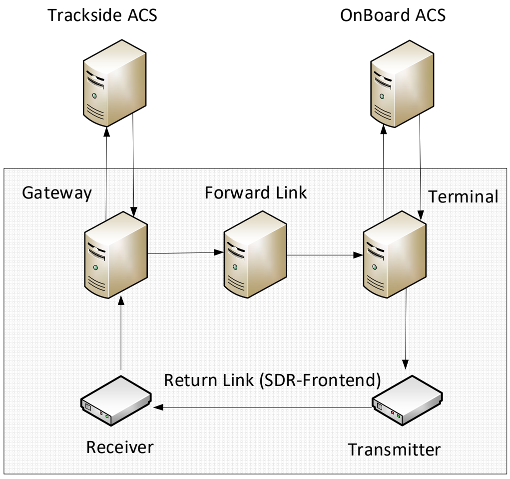


Figure 4-3: SatCom SDR prototype setup

We provide a MAC and a PHY layer implemented in C/C++ for each the gateway and the user terminal running on dedicated PC. Two USRP N210 are used as radio-frequency frontend to convert the data into the desired radio waveform. The USRPs are connected by a coaxial cable equipped with a 35dB attenuator in order to protect the RF component from high currents. An Octoclock is used for time reference. A satellite channel emulator adds a fixed delay (200ms) and a certain packet drop rate.

We assume a wide-band system for the forward link which is not limited by resources and simply forward the messages on this link. For the return link, the situation is different where multiple users transmit in an uncoordinated way with short signaling messages, as it is the case for ETCS. Furthermore, in order to provide a cost-efficient solution enabling equipment for a large number of trains, the terminal complexity must be kept low. Random Access (RA) schemes are a suitable solution for such characteristics and fit better than typical applied TDMA schemes. We implemented Contention Resolution ALOHA (CRA) [10]. CRA belongs to a family of modern RA schemes for data transmission and uses proactive replications of packets and successive interference cancellation for achieving a high spectral efficiency. No channel sensing or any advanced handshake procedure to grant resources are necessary. In order to resolve possible channel contention when multiple users (trains) access the same resource at the same time, advanced signal processing, error correction and interference cancellation are exploited. All these advanced techniques entail additional complexity that is confined to the receiver side. The prototype is the first in the railway sector to implement a frame- and slot-asynchronous uncoordinated RA protocol.

## 4.4 Lab-Tests

The SatCom SDR prototype was integrated as bearer next to 4G in lab within the regional line demonstrator. The integration was done via VPN connecting the SatCom prototype at DLR premises in Germany with the demonstrator at Hitachi's premises in Italy. As application an ETCS traffic emulator was used. The SatCom prototype adds delay which is characteristically for a SatCom channel in geostationary orbit and is expected to be much higher than the delay caused by the remote integration. Therefore, no negative effects are expected by the remote integration for the integration tests. For performance tests it is recommended to have a local integration.

Several integration tests have been performed using pings: Bidirectional connectivity initiated at the wayside ACS and Bidirectional connectivity initiated at the on-board ACS. On Average 440ms was needed per transmission which matches the set delay for a GEO satellite plus some additional delay for the remote integration via VPN. Furthermore, packet inspection tests have been performed. The test was passed and the expected packets where received with the set channel impairments. Figure 4-4 presents the achieved bitrate on forward and return link path. For ETCS a minimum of 4kbit/s is required which was constantly achieved.

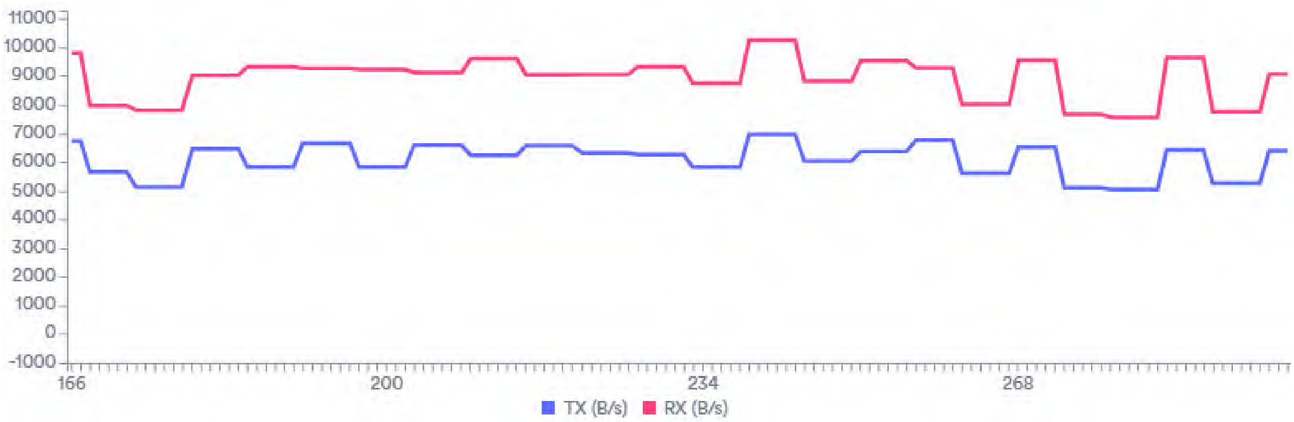


Figure 4-4: SDR SatCom Prototype results network chart [2]

The test results attest a successful integration of the SDR SatCom prototype. By the use of a traffic emulator, it could be verified that the SatCom prototype can be used for ETCS traffic. The network chart showed a smaller transmission rate at the return link which is expected since here the SDR link is used. The data rate still is above the limit defined in the user requirements, hence we could verify that the system can be used for ETCS traffic.

## 4.5 Regional and Freight Demonstrator Field Test Set-up

These results in lab using the SDR prototype motivated further tests in field using operational commercial SatCom systems. Figure 4-5 depicts the logical network architecture used for the Regional and Freight demonstrator field test, specifying the actual number and types of the network connections at disposal on the ACS gateway and the three key applications that have been chosen for the field test campaign (Channel Characterization Tool (CCT) for testing and monitoring, ETCS/ERTMS and VoIP for wayside communication).

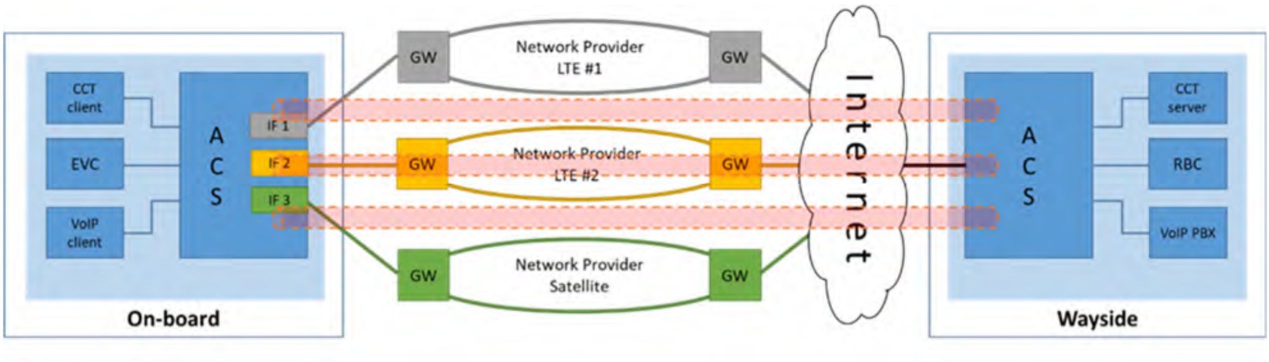


Figure 4-5: ACS regional line field test setup

On the train, two embedded LTE modems and one external satellite modem are available; each client application device has been configured with a static private IPv4 address. The on-board ACS gateway and the wayside site are logically connected through three network tunnels, that are build and manages by the ACS platform. Both on-board and wayside ACS gateway will have an assigned public static IP address to be reachable during the tests. A test train will be used on which's rooftop two combined antennas (2G/3G/4G/GSM-R/GNSS) and a HUGHES SatCom antenna mod. C11 connecting to BGAN service from Inmarsat will be installed for the trackside/on-board data exchange. LTE1 service provider is TIM, LTE2 Vodafone. Figure 4-6 shows the mechanical solution adopted by the ACS onboard GW.

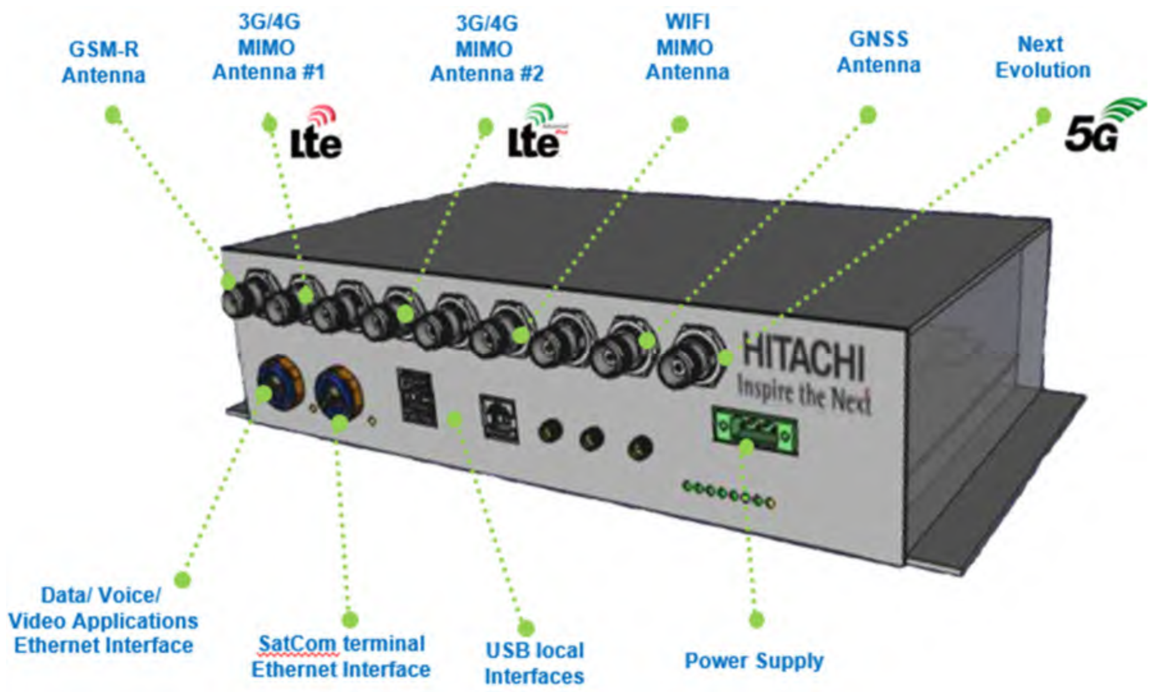


Figure 4-6: ACS onboard GW hardware schematic

The trial will be performed in the track between Novara and Rho, Lombardy, in the North of Italy. Its integrated in the double track Railways line 153km long connecting Torino and Milano and managed by RFI. The Novara-Rho Pilot-Line has been selected by RFI for being the first application of an ERTMS Level 2 system based on GNSS localization.

Preliminary radio surveys on the test track route were conducted within the scope of the SAT4TRAIN project (see Figure 4-7). The train runs were based on a double-journey measurement campaign during which the performances of an ETCS emulator were logged to register the status of bearers along the path and the functionality of signaling protocols implemented by the ETCS emulator.


Figure 4-7: Connectivity Journey 1: Novara – Milano-Lambrate (Green: no criticality, Yellow: some criticality, Red: criticality)

The ETCS emulator registered 'critical conditions' in three sections of the path. All these events are linked to situations when the train were close to or went under motorway overpasses or was approaching arrival station passing in a zone surrounded by buildings. In this situation, all bearers experienced quality degradation, which resulted in packet loss/corruption; these impairments did not cause faults in the Euroradio protocols due to retransmissions occurred at either TCP or applicative layer. The second measurements varied and seem to confirm the time variant nature of retail LTE network quality of service.

Additional field test will soon be performed providing more results on the performance using SatCom for the ACS.

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## 4.8 Authors

**Benjamin Barth**, M.Sc., Scientific Researcher, German Aerospace Center (DLR), graduated in Electrical Engineering at the Technical University Berlin in 2014. Since 2015 he has been with DLR's Institute for Communications and Navigation. His research activity deals with integration of satellite and terrestrial networks and system engineering for communications for railways and public protection/disaster relief.

E-Mail: Benjamin.Barth@dlr.de

**Marcel Grec** received his M.Sc. degree in Electrical Engineering from the Technical University of Munich (TUM) in 2016. Since 2018, he has been with the Institute of Communications and Navigation, German Aerospace Center (DLR) working on EU and ESA projects concerning software defined radio. Recently his focus shifted towards SatCom participating at the 9th Advanced Satellite Multimedia Systems Conference (ASMS) and 15th Signal Processing for Space Communications Workshop and at the TUM-COM Ultra-Reliable Low-Latency Communications and Applications for 5G Workshop. His main research interests include rateless codes, software defined radio and random access. During the past years, he has been with the same institute where in the context of his internships, B.Sc. and M.Sc., efficient implementations of ML decoding algorithms for fountain codes and their complexity analysis have been carried out.

E-mail: Marcel.Grec@dlr.de

**Stefan Erl, M.Sc,** Scientific Researcher, DLR. He graduated in Electrical Engineering at the Technical University of Munich in 2011 and has been with the Institute for Communications and Navigation of DLR since 2011 working on broadband satellite communication protocols, DVB-S2/RCS2 and resource allocation algorithms for multibeam satellite systems.

E-Mail: Stefan.Erl@dlr.de

**Norma Montealegre**, Dr. rer. nat., has professional experience in the research and aerospace industry. Prior to joining the German Aerospace Center, she did research at the European Space Agency and the Heinz Nixdorf Institute. She developed FPGA designs such as a test module for the storage system of a satellite and a multi-FPGA platform for space systems. She got her doctorate from the University of Paderborn working in the area of self-repairing hardware systems and managed for the Heinz Nixdorf Institute the last phase of the inter-university project Reconfigurable Computing Systems financed by the German Research Foundation.

E-Mail: Norma.Montealegre@dlr.de

**Alessandro de Rienzo, M.Sc.** degree in Telecommunication Engineering at the University of Napoli in 2007. Since 2008, he has been working with Hitachi Rail (former Ansaldo STS) on the design and delivery of Telecommunication systems in Railways projects, especially focused on the train to ground communication systems. He manages the Data Communication System Competence Center in Hitachi Rail and he is the TLC technical representative in the EU innovation projects leading to the standardization and the validation of the platforms enabling the migration towards FRMCS.
E-Mail: Alessandro.derienzo@dlr.de

# 5 ETCS testing environment including ACS and saboteur

*Nerea Fernández-Berruetea, Jaizki Mendizabal Samper;*
*CEIT, Donostia / San Sebastián, Guipúzcoa, Spain*
*Benoît Faup, Alain Maintrot; KONTRON, Montigny Le Bretonneux, France*

## 5.1 Introduction

GSM-R is an interoperable track-to-radio technology used by many infrastructure managers (IM) and railways undertakings (RU) for operational voice communications. GSM-R also acts as the data bearer for the European Train Control System (ETCS) [1].

It has been widely adopted as a standard for rail communication and signaling, and has proven to be effective in improving safety and efficiency in railway operations. In fact, it is still widely used and has been implemented in many countries around the world. However, there may be persuasive reasons to replace GSM-R because of its performance (low link rate, delay, and interferences), reliability, security limitations, and maintenance issues being its end of support planned by 2030 onwards. Due to these reasons, it can be stated that GSM-R does not accomplish the requirements for the current applications. Then, the desire to adopt more advanced and innovative technology is the requirement to support the increasing demand for digital services and connectivity in the railway industry and the need to address the limitations and challenges of GSM-R. Therefore, a need for faster and more reliable communication and signaling systems is stated.

As a consequence, the railway industry needs to evolve and adopt new technologies, there is a growing need for more advanced communication and signaling systems that can support increased demand for data, connectivity, and digital services. This is leading some railway companies to consider alternative solutions that can offer improved performance, efficiency, and functionality.

Before making a decision to replace GSM-R, it is important to consider the costs, the benefits of alternative technologies, the specific needs, and priorities of each railway company or system, as well as the compatibility and interoperability with existing systems and equipment. Therefore, an evolution of the current communication technology is needed. Within S2R the Adaptable Communication System (ACS [3]) was specified to test technical concepts which can be used in the Future Railway Mobile Communication System (FRMCS) [2].

However, testing new communication systems technologies in real conditions via traditional testing methods along railway tracks is highly time-consuming, very expensive, and potentially disruptive to railway operations. Because of this reason, the goal of "zero on-site testing" Work Package, within the Shift2Rail program, is to develop new technologies and methods for testing and validating railway equipment and systems without the need for physical testing on the railway track. In fact, the key objective of zero on-site testing, is to perform functional and non-functional tests (component test, integration test, and system test) in the laboratory, instead of testing on-site, in order to save time and costs without compromising on safety [3]. By reducing the need for on-site testing, the program aims to speed up the development and deployment of new railway technologies and systems, improve their reliability and safety, and reduce their impact on the environment.

Then, in order to reach the main goal of zero onsite testing different prototypes have been designed, developed, and implemented within Shift2Rail. Nevertheless, this paper only focuses on Performance Validation and stress testing and focused especially on the GSM-R network and the next-generation network protoype.

## 5.2 Enhancement of the prototype ACS

In X2Rail-3 [4] a prototype for Performance Validation and stress testing focussed especially on the GSM-R network and the next-generation network was defined and implemented [5]. The configuration schema from this project was the one shown in Figure 5-1.

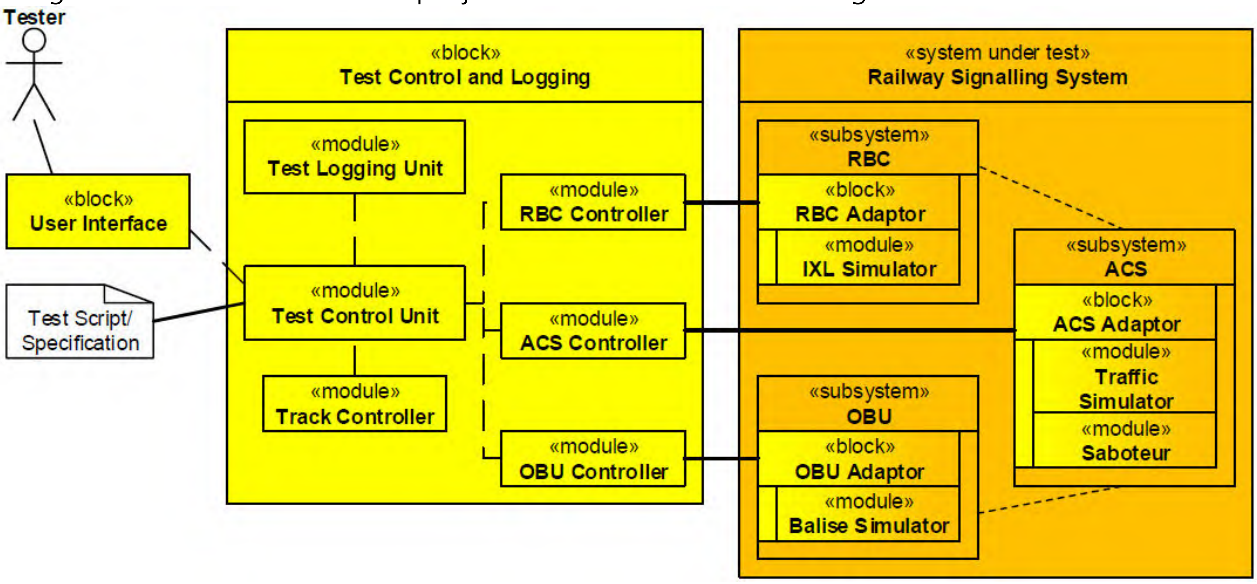


Figure 5-1: Configuration schema of the prototype for Performance Validation and Stress Testing

For X2Rail-5 [6] the goal is to follow up on the implementation of X2Rail-3 [4] to enhance the mentioned prototype. Nevertheless, not every module shown in the schema from X2Rail-3 [4] could be implemented. The current schema for X2Rail-5 is shown in Figure 5-2. In this case, the RBC and OBU are replaced by TS/OB ETCS-like and GSM-R by FRMCS. Moreover, the TCL has been implemented as a TCL light without the whole functionalities.

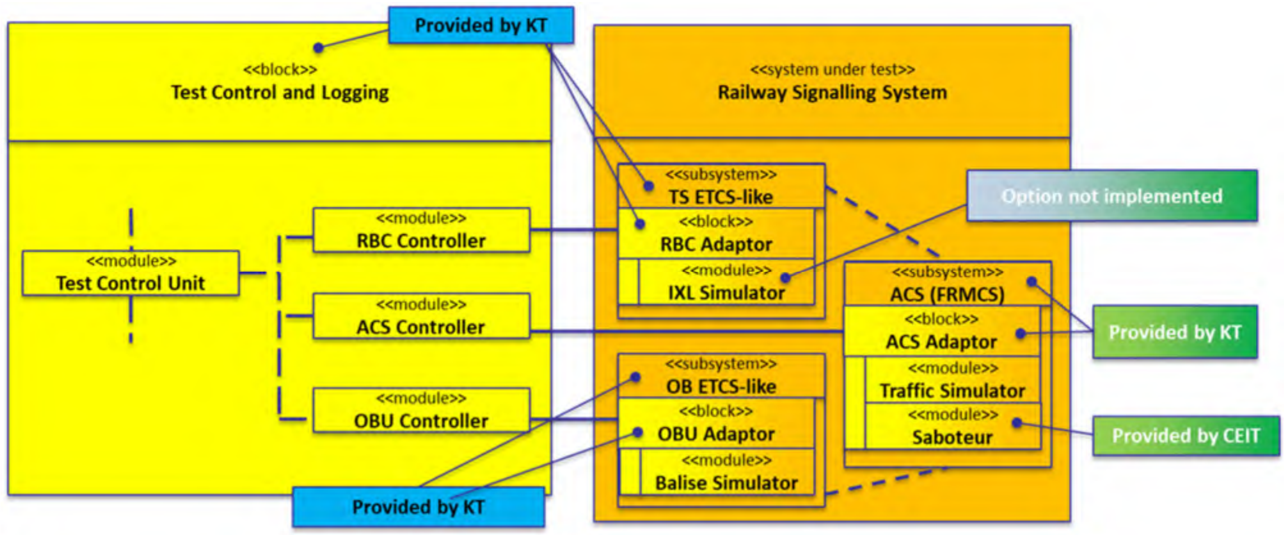


Figure 5-2: Configuration schema for X2Rail-5 WP9

Then, this paper focuses on the TCL "light", ACS adaptor, OBU adaptor, RBC adaptor and the saboteur.

## 5.3 Prototype environment

The current prototype environment for the improvement of the mentioned prototype is the following one shown in Figure 5-3. In a preliminary integration between the saboteur and the ETCS environment, the Appli OB sends information to the Appli TS.

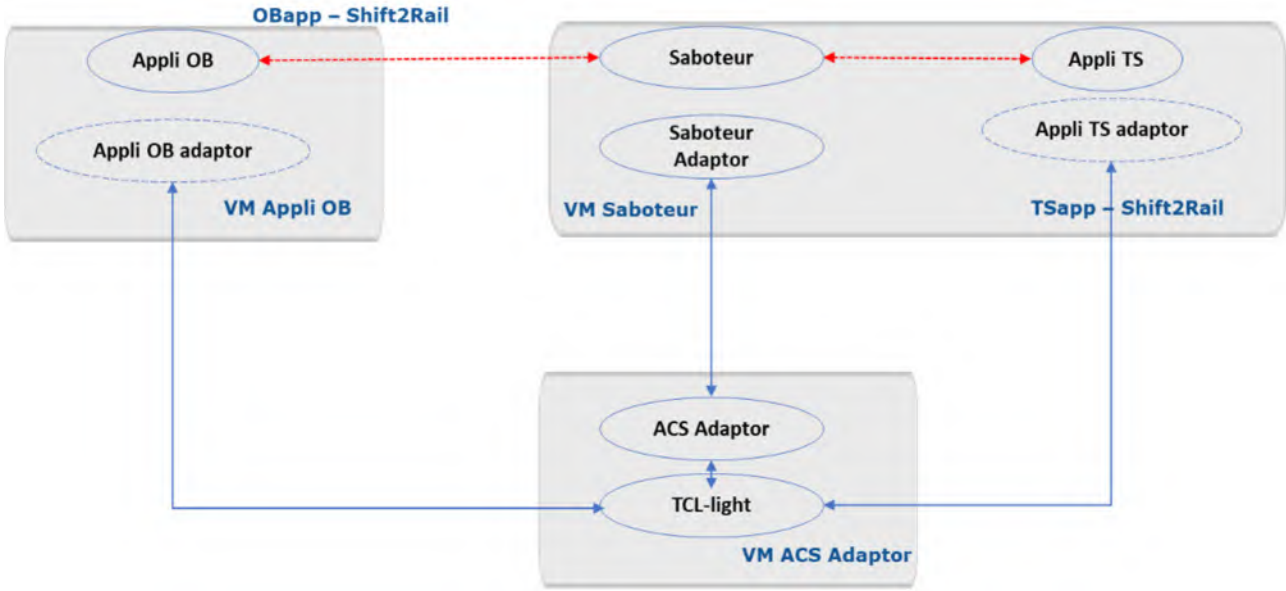


Figure 5-3: Current prototype environment

The purpose of this prototype is to integrate it into the 5G rail network including ToBA, TS-GW and a 5G network which will be explained in Section 5 Future works.
In the following subsection further details of the Saboteur are provided.

**Saboteur**
The saboteur is a module in the target prototype, designed and developed within X2Rail-3 [4] and X2Rail-5 [6]. It injects faults in the communication link so that, as the main purpose of this

prototype is to test the performance of the communication, the saboteur is placed between the on-board and trackside application.

Moreover, considering [7] as the basis, the control information to the saboteur is sent by a TCL via XML-RPC protocol [8]. However, as in X2Rail-5 [6] a real TCL is not available, a limited TCL has been developed called TCL light. This TCL light module sends the desired configuration information to the saboteur. If the configuration is set properly, the saboteur sends the corresponding response.

Faults

Different faults can be configured to the saboteur. Depending on this fault, the traffic will behave differently. The types of faults are the following:

1. Remove: remove totally the packets in the communication link, that is to say, no message will be sent from OB to TS and vice versa.
2. Delay and jitter: in this case, the delay will be always configured in the communication link. Nevertheless, the jitter will only be configured if there is a delay available.
3. Packet loss: this field indicates the percentage of packet loss that the communication link will have.

Some of these faults can be configured by overwrite mode; if a delay and jitter fault has already been configured, the packet loss can also do so.

TCL-Saboteur messages

The possibilities for the configuration of the faults are explained above. Consequently, the control messages from the TCL to the saboteur in order to assure this desired configuration have been defined via XML-RPC as [7] does. These messages are:

- "sab.status": the TCL request the status of the saboteur; if the saboteur has already been configured.
- "sab.activation/deactivation": activate or deactivate the saboteur. If the status of the saboteur is deactivated, it will act as a router forwarding the messages; no effect will be applied to the traffic.
- "sab.configure": this message contains the type of fault to be configured to the saboteur. The types of faults are the ones mentioned in the faults section.
- Each of these messages has a response to notify the TCL light that the request has already been processed.

## 5.4 Results

The preliminary results obtained by the enhancement of the prototype are explained below. The setup of these preliminary results is the one explained in Figure 5-3, with the 5G network not still integrated. Then, in order to integrate both modules, some tests have been performed. Firstly, the verification of the test concerning the integration of the saboteur with the environment was done. In order to perform a set of tests, the ping tool has been used for this purpose. The followed test methodology was consisting of two parts: one testing the integration without configuring a fault and the other one with the configuration already set. The result without a configuration is the one shown in Figure 5-4. It can be seen that there are just few milliseconds of delay due to the time for transmitting and receiving the packet.

```
30 packets transmitted, 30 received, 0% packet loss, time 463ms
rtt min/avg/max/mdev = 0.353/0.406/0.481/0.026 ms
```

Figure 5-4: Result from the ping without configuration

Next, the following configuration of the saboteur was sent in a “sab.configure” message:

- Delay = 50 msec,
- Jitter = 10 msec,
- Packetloss = 0.0001 (ie. 0.01%)

This configuration is correctly set as Figure 5-5 and Figure 6 shows the response message and the status of the saboteur respectively.

In order to test every parameter, a sequence of 15000 packets has been sent; in order to notice the packet loss.


```
SABOTEUR -> ACSADAPTOR: sab.statusResponse { timeStamp="20230124T09:38:52" idMessage=7 SabModId=100 state=2 message="status infor
mation" }
<?xml version="1.0" encoding="ISO-8859-1"?><methodResponse><params><param><value><array><data><value><dateTime.iso8601>20230124T0
9:38:52</dateTime.iso8601></value><value><int>7</int></value><value><int>100</int></value><value><int>2</int></value><value>statu
s information</value></data></array></value></param></params></methodResponse>
```


Figure 5-5: sab.statusResponse message


```
ACSADAPTOR -> TCL: INIT.state { timeStamp="20230124T09:38:52" ACSUnitId=100 state=0 }
<?xml version="1.0" encoding="ISO-8859-1"?><methodResponse><params><param><value><array><data><value><dateTime.iso8601>20230124T0
9:38:52</dateTime.iso8601></value><value><int>100</int></value><value><int>0</int></value></data></array></value></param></params
></methodResponse>
```


Figure 5-6: status of the saboteur

The results of the configuration, shown in Figure 5-7, are an average delay of 50 ms and a packet loss of approximately 0.01% which matches with the configured.

```
15000 packets transmitted, 14998 received, 0.0133333% packet loss, time 214871ms
rtt min/avg/max/mdev = 40.354/50.575/94.561/5.793 ms, pipe 7
```

Figure 5-7: Result of configuring the saboteur with ping tool

Then, the application from the on-board sends TCP and UDP traffic.

First of all, the application without configuring the saboteur is performed. As result, the delay is close to 0 ms and there is no packet loss as Figure 5-8 shows. In this specific test, the traffic sent was UDP one; it does not take effect on the type of traffic if no fault is configured.


Figure 5-8: traffic UDP sent with no configuration in the saboteur

After the testing without faults in the saboteur, the tests are carried out with different faults and TCP or UDP traffic.

Firstly, UDP traffic was sent having configured the saboteur via sab.configure with the following faults:

- sab.configure(delay=50 ms, jitter=10 ms)
- sab.configure(packetLoss=0.01, being 1%)


Figure 5-9: Results from the first configuration of the saboteur with UDP traffic

Figure 5-9 shows the results with the mentioned faults. The packet loss is approximately 1%, being exactly 0.8%. In order to obtain a more accurate packet loss, more packets should be sent. Moreover, the delay can be shown in the same figure, being the average delay of approximately the one configured in the "sab.configure" message, that is, 50ms and a jitter of 10ms. Figure 5-10 shows the configuration of the saboteur (how it is configured) and the configuration on the TCL side.


Figure 5-10: First configuration of the saboteur

Secondly, TCP traffic was sent having configured the saboteur via sab.configure with the following faults:

- sab.configure(delay=50, jitter=10)
- sab.configure(packetLoss=0.0001, being 0.01%)

The obtained results from the test with TCP traffic correspond to no packet loss. Nevertheless, this is because of the nature of TCP; if TCP is losing one packet, it will be retransmitted. Consequently, the loss of one packet could not reflect a packet loss but a high maximum delay as the following line shows (max delay of 327.606 ms).

upTcp018: TX=30000 RX=30000 RTD min/max/avg: 40.445/327.606/50.73707 ms

Thirdly, UDP traffic was sent having configured the saboteur via sab.configure with the following faults:

- sab.configure(delay=200, jitter=50)
- sab.configure(packetLoss=0.01, being 1%)


Figure 5-11: Second configuration of the saboteur


Figure 5-12: Results from the second configuration of the saboteur with UDP traffic

Figure 5-12 shows the final packet loss being 0.8% which is approximately 1%. In order to obtain a more accurate packet loss, more packets should be sent. Moreover, the delay can be shown in the same figure, being the average delay of approximately the one configured in the "sab.configure" message being 200ms and a jitter of 50ms.

Finally, TCP traffic was sent having configured the saboteur via sab.configure with the following faults:

- sab.configure(delay=200, jitter=50)
- sab.configure(packetLoss=0.0001, being 0.01%)

The obtained results from the test with TCP traffic correspond to no packet loss. Nevertheless, as in the previous test, this is because of the nature of TCP; if TCP is losing one packet, it will

be retransmitted. Consequently, the loss of one packet could not reflect a packet loss but a high maximum delay as the following line shows (max delay of 627.286 ms).
upTcp020: TX=30000 RX=30000 RTD min/max/avg: 150.689/657.286/201.17856 ms

## 5.5 Future works

X2Rail-5 is ongoing at the time of writing this abstract; therefore, no setup of the whole network was available. In future works, the modules concerning ACS and saboteur will be integrated with the network corresponding to the 5GRail project [9] as Figure 5-13 shows.

The 5GRail project is a research and innovation project focused on developing 5G technology for the railway industry. The project aims to demonstrate the benefits and feasibility of using 5G technology in railway operations, including communication and signaling, onboard services, and remote monitoring and control.

After that, tests with the saboteur passing through the 5G network will be performed.

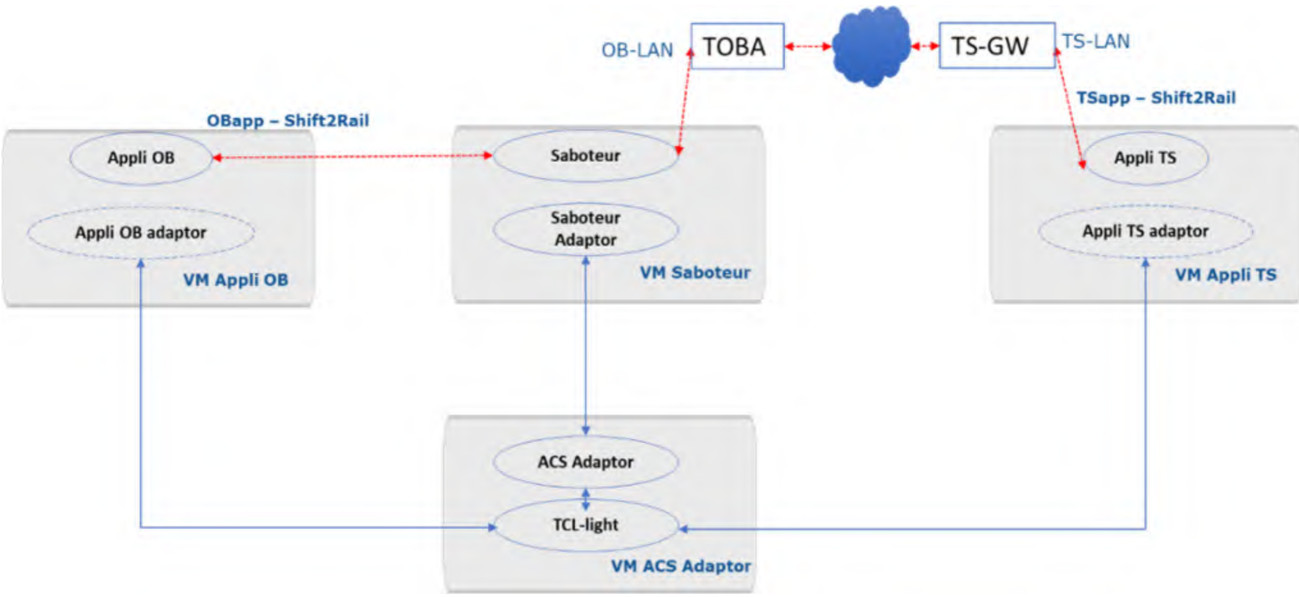


Figure 5-13: ETCS environment through the 5G network

The next steps for this prototype are the complete integration into the 5G network and the testing of the application within it. In this way, the saboteur will inject faults in the 5G network, allowing to know the final effect that can cause it in the ETCS application.

## 5.6 Conclusions

After testing different test cases with the prototype, some conclusions can be raised.

It is shown in this paper that the saboteur has an impact in no matter type of traffic being ICMP (integration phase), TCP, or UDP (testing). Nevertheless, depending on the traffic the impact is not the same. For UDP traffic, the saboteur has an effect on packet loss. However, in the TCP traffic, the impact is shown in terms of delay of the packet already sent.

Moreover, the integration of the tested network into the 5G one will bring interesting results for the future of on-site testing, and, for sure the future of railway communications.

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## 5.8 Acknowledgements

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## 5.9 Authors

**Nerea Fernández-Berrueta** received the M.Sc. degree in tele-communications engineering from the Faculty of Engineering, University of the Basque Country, Bilbao, in 2016 and the Ph.D. degree from TECNUN (University of Navarra, San Sebastián, Spain) in 2022. She joined the CEIT-BRTA Research Centre, San Sebastián, in 2017. Her research activity lies in the field of railway signalling, especially in zero on-site testing and adaptable communication systems in the Transport and Sustainable Mobility group. She is now actively participating in H2020 European funded, such as Shift2Rail projects in railway communications and testing: X2Rail-5, and in projects related to 5G technology such as 5G Euskadi.

e-mail: nfernandez@ceit.es

**Jaizki Mendizabal** received his M.Sc. and Ph.D. degrees in Electrical Engineering from TECNUN (University of Navarra, San Sebastián, Spain) in 2000 and 2006 respectively. He joined Fraunhofer Institute (Germany) and SANYO Electric Ltd, Japan as RF-IC designer. Nowadays, he is at CEIT-BRTA, in San Sebastián (Spain) where his research interests include communications and electronic systems. He is lecturing "Communications Electronics" and "Communications via Radio" at TECNUN (University of Navarra).

e-mail: jmendizabal@ceit.es

**Benoît Faup** is Product Line Manager and Life Cycle Manager at KONTRON for Railway. After a Master's degree in International Trade and a multi-year experience in logistics, Benoît joined Nortel in 2000 where he held various positions of product management, project management for both software and hardware and took the lead of interoperability testing among the product group. With Kontron since 2019, he has specialized in Product Life Cycle Management from introduction to end of life in a whole range of domains (Access, Core, Cab Radio etc) developing specific knowledge in product development phases and qualification processes, among which product validation and interoperability. Benoît is also KONTRON NVIOT Steering group representative and responsible for the KONTRON contribution in TD2.6 zero on-site testing work package of the X2Rail-1, -3 and -5 project.

e-mail: Benoit.Faup@kontron.com

**Alain Maintrot** is System Architect in KONTRON R&D. After a degree in computer science and several missions in the telecommunication companies, he joined Nortel in 1998 where he held various positions from designer to team leader and product architect to system architect. As a Nortel, Kapsch and now KONTRON employee, Alain is also involved as a technical expert in standardization for Regulatory Bodies (3GPP, ERA, GSM-R Industry Group, UIC, …). He is currently contributing for KONTRON in TD2.6 zero on-site testing work package of the X2Rail-3 and -5 project.

e-mail: Alain.Maintrot@kontron.com

# 6 Cyber security studies on the ATO and NG-TCMS TD's

*Dimitrios Sisiaridis; Alstom, Charleroi, Belgium*
*Sai Lokesh Posa, IRT Railenium, Famars, France*

## 6.1 Introduction

The X2Rail-5 program aims to develop key technologies to foster innovation in the fields of railway signaling, automation, telecommunications, testing methodologies, and cyber security as part of the Shift2Rail IP2 strategy towards an intelligent, real-time, flexible traffic control management and decision support system. It includes full technology demonstrators and ITDs. An important focus of Shift2Rail is demonstration activities, which are needed to deliver a quantified impact, but also to provide guidance on the most efficient combinations of these technologies and assess the potential for improvement to the national and EU transport network.

This document provides a summary of the generic requirements for creating and validating a cybersecurity framework for railway systems. Specifically, X2R-5/WP11 involves the validation of the cybersecurity framework and the creation of an incident report that analyzes cyber-attacks against railway systems. As the interconnected digital railway network at the European level grows and continues to grow, security risks will increase. Consequently, there is an increasing need to address these cyber-security threats in railway systems.

The objective of this technology demonstrator is to achieve the optimal level of protection for signalling and telecom systems against any significant threat in the most economical manner possible like the protection from cyber-attacks and advanced persistent threats coming from outside. More specifically, we analyze cybersecurity risk on ATO GoA2/3/4 and on the NG-TCMS by assessing different threat scenarios and determining how the risk will be exploited. The risk assessment methodology builds upon the previous X2R-3 Simplified Risk Assessment methodology: the impact criteria have been improved to match the Signalling and the NG-TCMS environments respectively. Furthermore, likelihood formulas are based on two factors which are combined: the attacker likelihood to launch a successful attack, as well as the target exposure due to identified vulnerabilities. The methodology aims to address attack paths, by looking into worst-case scenarios. In both TDs (ATO, NG-TCMS), special attention has been given to the management of Safety functions when it comes to cybersecurity attacks, which were not included in the previous analysis in X2R-3.

## 6.2 Objective

The primary goal of task T11.2 in WP11 is to complete and validate the work done by the TD2.11 during the projects X2Rail-1 and X2Rail-3 through the completions and assessment of the demonstrators started in X2Rail-3 (ATO GoA2, ATO GoA3/4, NG-TCMS).

This task11.2 focuses on the Cybersecurity Risk Assessment methodology in order to identify the Primary and Supporting Assets that will be necessary for the Technical Demonstrators to get the system under consideration.

As a result of the applied risk assessment approach, the assessor is able to estimate likelihood, and estimate the risk level, by considering the worst damage potential if a core system function is lost, due to a successful attack on either the confidentiality, integrity or the availability of the system. The threat landscape utilizes Microsoft's STRIDE threat model. The methodology itself is fully aligned with IEC-62443-3-2 [5] and TS 50701 [2] as well as with the NIST Guide for performing risk assessments [11].

As part of the risk assessment, however, security protection and countermeasures for ATO and NG-TCMS will be implemented. In the case of ATO, proposed countermeasures will be the outcome of the risk assessment. For the NG-TCMS, we will assess the CONNECTA-3 group proposed countermeasures, against the determined target security level from the risk assessment. For both TDs, a list of recommendations for hardening shall be created. All technical requirements are defined according to the IEC/ISA 62443-3-3 [6], at the zone level, and to IEC/ISA 62443-4-2 [7], at the component level.

## 6.3 Automatic Train Operation (ATO)

Automatic train operation (ATO) refers to the system that allows a train to operate without direct human intervention. The degree of automation is indicated by the Grade of Automation (GoA), up to GoA4 in which the train is automatically controlled without any staff on board. Different levels of grade of automations can be found in the below table:

Table 6-1: ATO different Grade of Automations.

| GoA | GoA Name | Train Operator | Description |
|---|---|---|---|
| **GoA1** | **Non automated train operation** | Train driver in the cab | The train is driven manually; but protected by automatic train protection (ATP). This GoA can also include providing advisory information to assist manual driving. |
| **GoA2** | **Semi-automated train operation** | Train driver in the cab | The train is driven automatically, stopping is automated but a driver in the cab is required to start automatic driving of the train, the driver can operate the doors (although this can also be done automatically), the driver is still in the cab to check the track ahead is clear and carry out other manual functions. The driver can take over in emergency or degraded situations. |
| **GoA3** | **Driverless train operation** | Train attendant on-board the train | The train is operated automatically including automatic departure, a train attendant has some operational tasks, e.g. operating the train doors (although this can also be done automatically) and can assume control in case of emergency or degraded situations. |

| GoA | GoA Name | Train Operator | Description |
|---|---|---|---|
| **GoA4** | **Unattended train operation** | No staff on-board competent to operate the train | Unattended train operation; all functions of train operation are automatic with no staff on-board to assume control in case of emergencies or degraded situations. |

## 6.4 ATO GoA2 – Standard Specification:

In this grade of automation, the driver is in the front cabin of the train observing the guideway and stops the train in the case of a hazardous situation. Acceleration and braking are automated, and the speed is supervised continuously by the system. Safe departure of the train from the station is the responsibility of the operations staff.

Below figure depicts the ATO GoA2 standard specification and presents supporting subsets for communication with other on-board and trackside sub-systems:

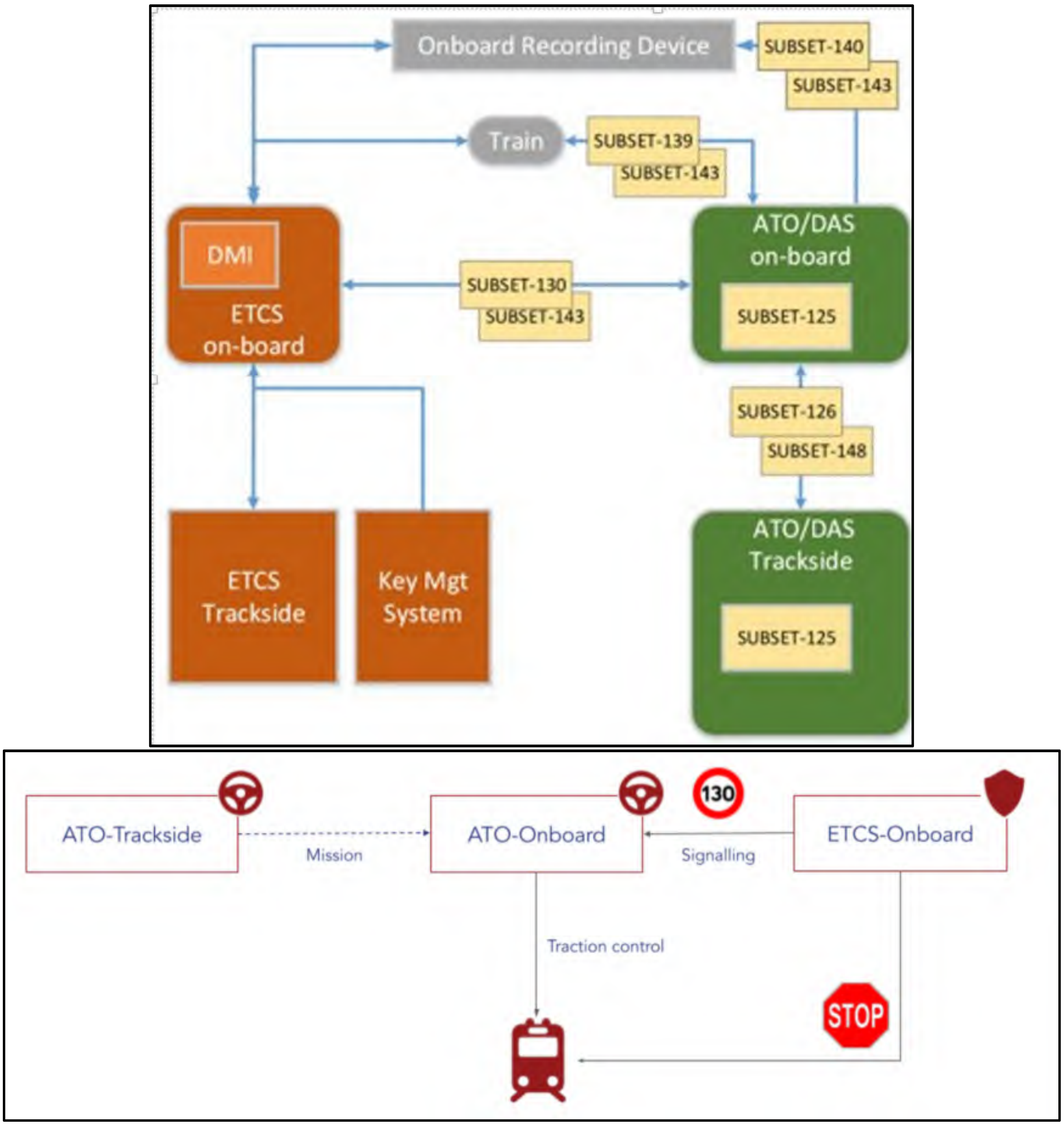


Figure 6-1: ATO GoA2 Standard Architecture, @ [13]

It has the two main components:

- **ATO-OB (SIL0)**: ATO-OB is onboard united, normally installed near to other ETCS units. It shall drive the train to respect the timetable provided by **ATO-TS** without breaking the safe limits imposed by ETCS-OB.
- The driver can use DMI to request the start and stop of automatic driving and other functions.
- **ATO-TS (SIL0)**: ATO-TS is a set of servers, connected to the TMS of the infrastructure manager. It shall generate and send journey profile and segment profile to **ATO-OB**

The Main interfaces for ATO-OB & ATO-TS:

- **ATO-TS – ATO-OB (SS-126 & SS-148)**: send journey profile and segment profile including timetable
- **ATO-OB – ETCS-OB (SS-130 & SS-143)**: Exchange ETCS train data (ID, category, mass, length), positioning information (From Balise), Supervision information (MA, Speed limits, brake deceleration, speed and acceleration information), driver's inputs (engage or disengage ATO) and DMI ATO indicators to driver.
- **ATO-OB – TCMS (SS-139 & SS-143)**: ATO-OB shall generate and send the signal for traction control and brake control (no emergency brake), also door control (optional).
- **ATO-OB – Onboard Recording Device (JRU) (SS-140 & SS-143)**: ATO-OB shall generate events records and send to on-board recording device (JRU).

## 6.5 ATO GoA3/4 – Standard Specification:

GoA3 operation, if any ATO GoA3/4 uses the same functions but the presence of a Train Attendant is mandatory for operation. The presence of Train Attendant is checked via a specific key reported to APM through TCMS. This is the only interface specific to GoA3. The Train Attendant has also a specific key to inhibit the door closure in case of incident, directly interfaced with TCMS.

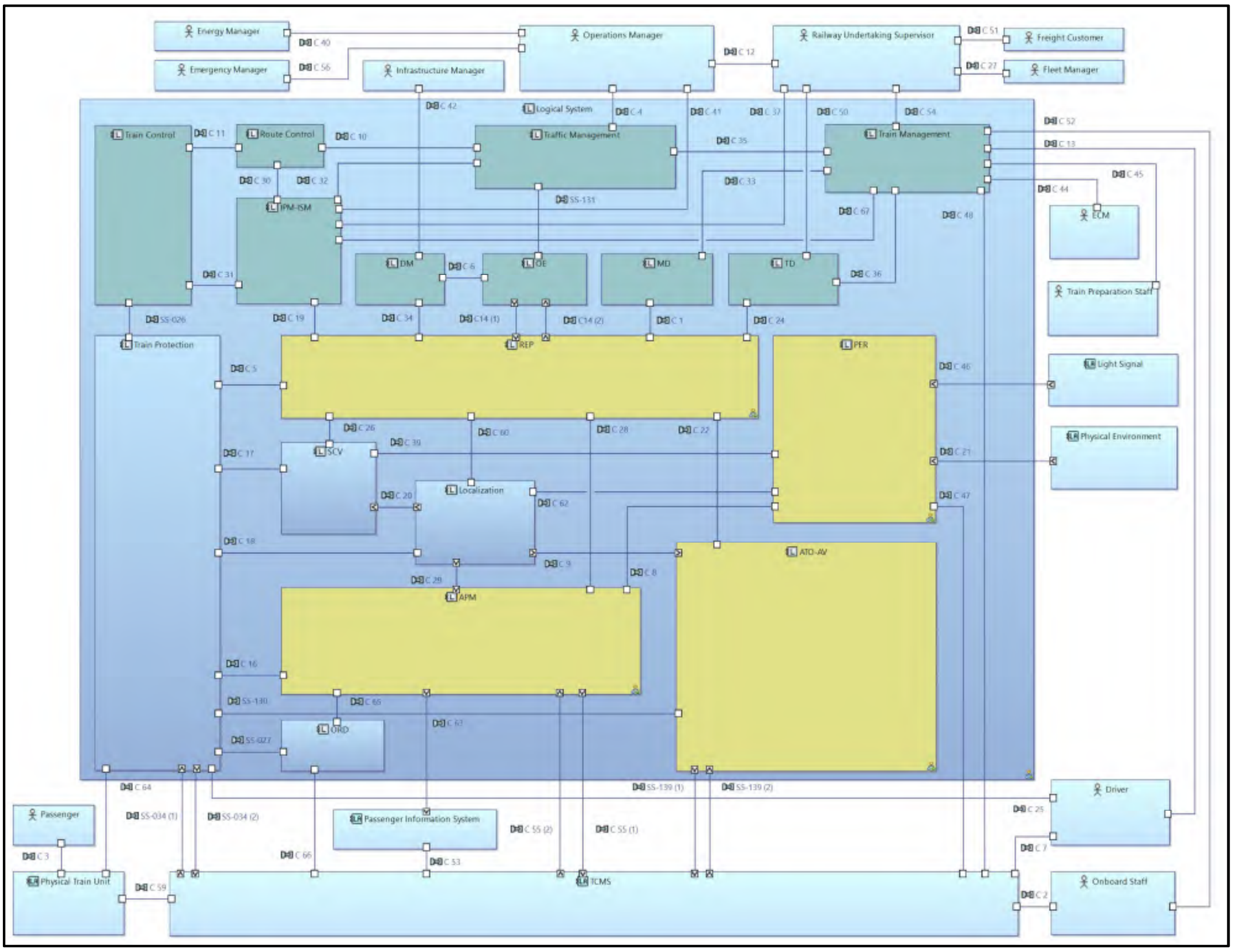


Figure 6-2: ATO GoA3/4 Standard Architecture Network @ [20].

An assumption has been made regarding the SIL level of ATO GoA3/4 modules: the highest SIL level equals to NOTE: an alternative would be to set the APM or the PER SIL level to 4, as it aims to substitute driver's and train attendant's responsibilities.

Main Components are [19] [20]:

- **ATO-AV (SIL2)**: ATO-AV is the evolution of GoA2 on-board component.
- **OE(SIL0)**: same as ATO-TS in GoA2, receive input from TMS, generate journey profile and segment profile.
- **APM (SIL2)** Automatic Processing Module: Substitutes driver and train attendant responsibilities for reacting in case of incident.
- **PER (SIL2)** Perception is a set of on-board modules sensing the Physical Railway Environment in place of the driver (SIL to be defined), e.g., Camera or radar. It can monitor the train environment in case any intrusion of a moving object. APM and PER together implement the functions ensured today by the driver in Main Line applications.

- **REP (SIL2)** Repository: Manages the communication with trackside and stores relevant information. Receive all the repository of info sent by trackside to/for ATO-AV, APM, SCV, including map, route, 3D information and risk zones on the line. Output from REP to APM is safety related.

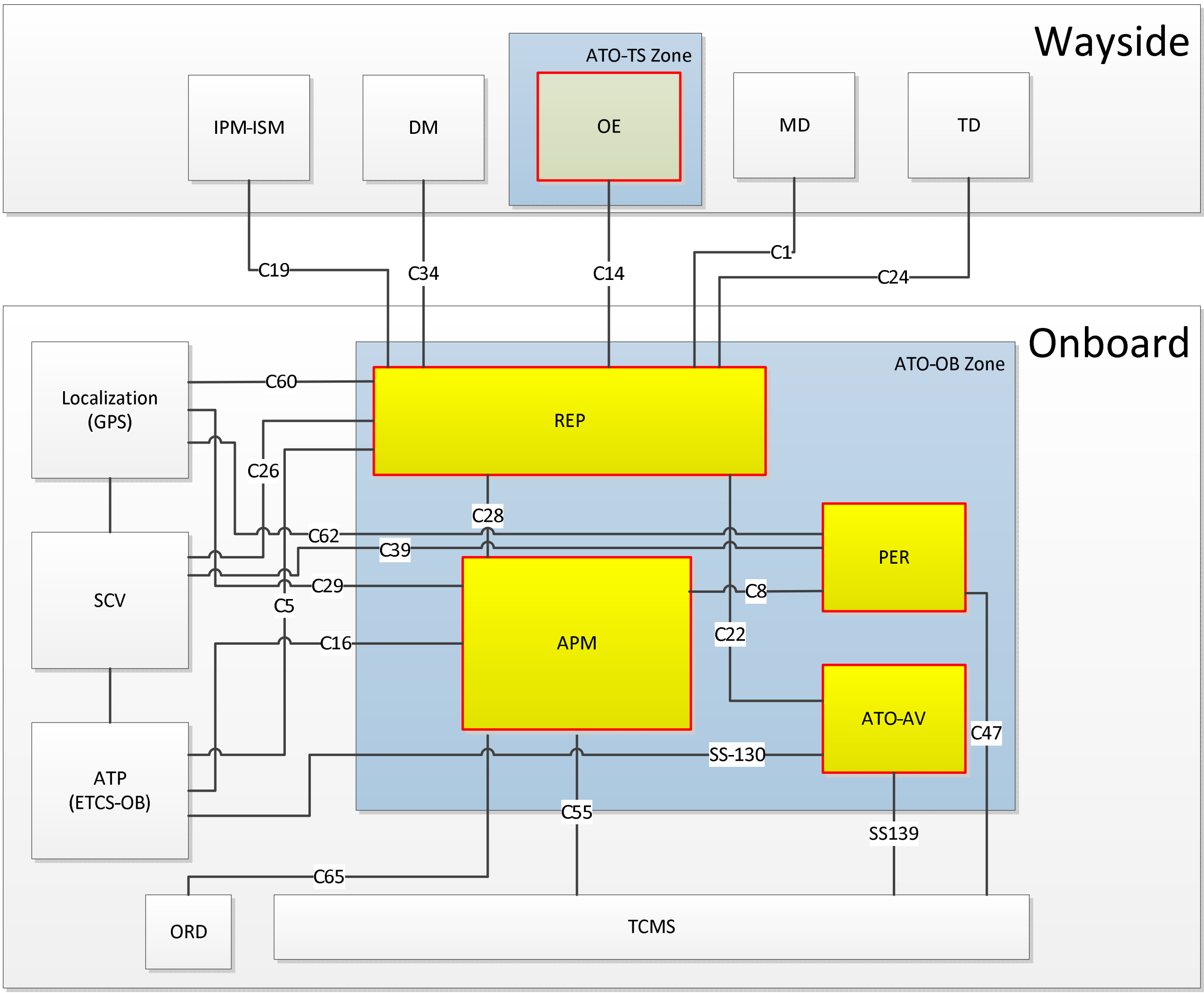


Figure 6-3: ATO GoA3/4 Zones & Conduits.

The above diagram shows how the communication will take place from wayside to onboard using different zones and conduits. The rectangle boxes represent zones and the lines connecting each zone is a conduit.

Function & Data:

- **Journey Profile**: Journey Profile (JP) is a concept developed in GoA2 and described in subset-125. Each JP details the journey as passing through a sequence of **Segment Profiles** (SPs), including mainly timing information and temporary infrastructure information.

- **Mission Profile**: The Mission Profile (MP) gives the list of path numbers agreed with Infrastructure Manager (IM) and defines the tasks to be performed on the Train Unit during the timeslots not dedicated to a journey.

The Mission Profile (MP) is modelled with a group of tasks planned and executed in a specific order. A task can be either associated to one journey or to one activity under the responsibility of a Railway Undertaking (RU). Only tasks associated to RU are inside of MP: this is done to have a clear division between IM's and RU's responsibilities. **APM** will execute the tasks defined in the mission.

## 6.6 NG-TCMS

The Train Control and Monitoring System (TCMS) is the brain and the communications backbone of the train, which has some essential roles on vehicle performance. It integrates and manages all on-board information; it makes train control decisions taking into account the global state of subsystems; it performs communication between equipment, between cars and between vehicles; and it integrates and interacts between different subsystems of the train.

New functionalities for the Next Generation TCMS (WP4) are a continuation of the developments on Train-2-Ground (T2G), Wireless Train Backbone (WTBN), and Wireless Consist Network (WLCN), which have been started in CONNECTA-1 and continuously improved throughout CONNECTA-2 [3]. CONNECTA-3 builds upon the results from the first two phases of CONNECTA project and sets the goal to drive technological development onwards and reaching higher Technology Readiness Levels (TRLs) by enhancing, finalizing, and validating the concepts and implementations of the previous phases.

Such activities aim to:

- Develop the ability to implement SIL4 functions in the TCMS to perform additional safety-critical tasks, removing safe train lines and integrating signaling equipment;
- Increase in the availability of trains related to the functioning of train control and monitoring by 50%;
- Develop the ability to couple any pair of multiple units of different types, which is a feature totally non-existent and can significantly increase line capacity;
- Support technologically the development of the "virtual coupling" concept, which can dramatically increase the capacity of lines, and;
- Reduce cost, time and effort in project engineering, integration and homologation phases by 50%.

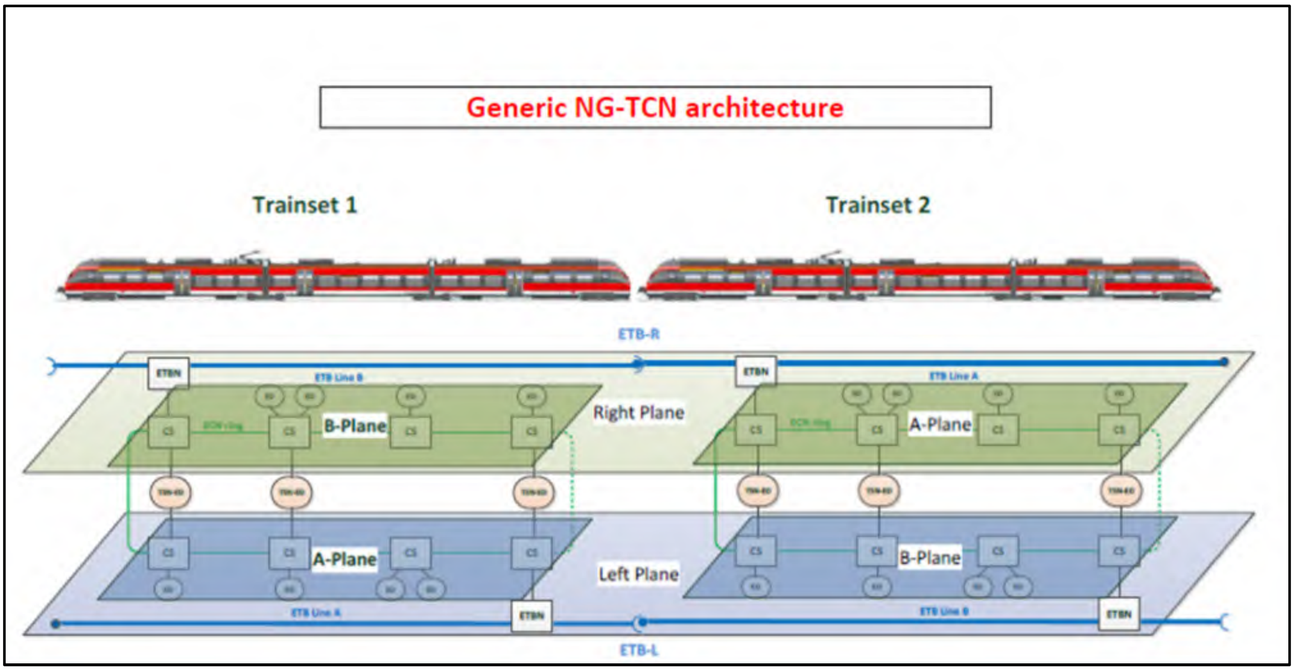


Figure 6-4: Architecture Diagram for NG-TCN @ [17].

**Conduits & Zones:**

In the below shown pictures the rectangular boxes represent the Zones and the lines through with two or more zones are connected is a Conduit. The communication of data is done through the WLAN routers and the network devices present.

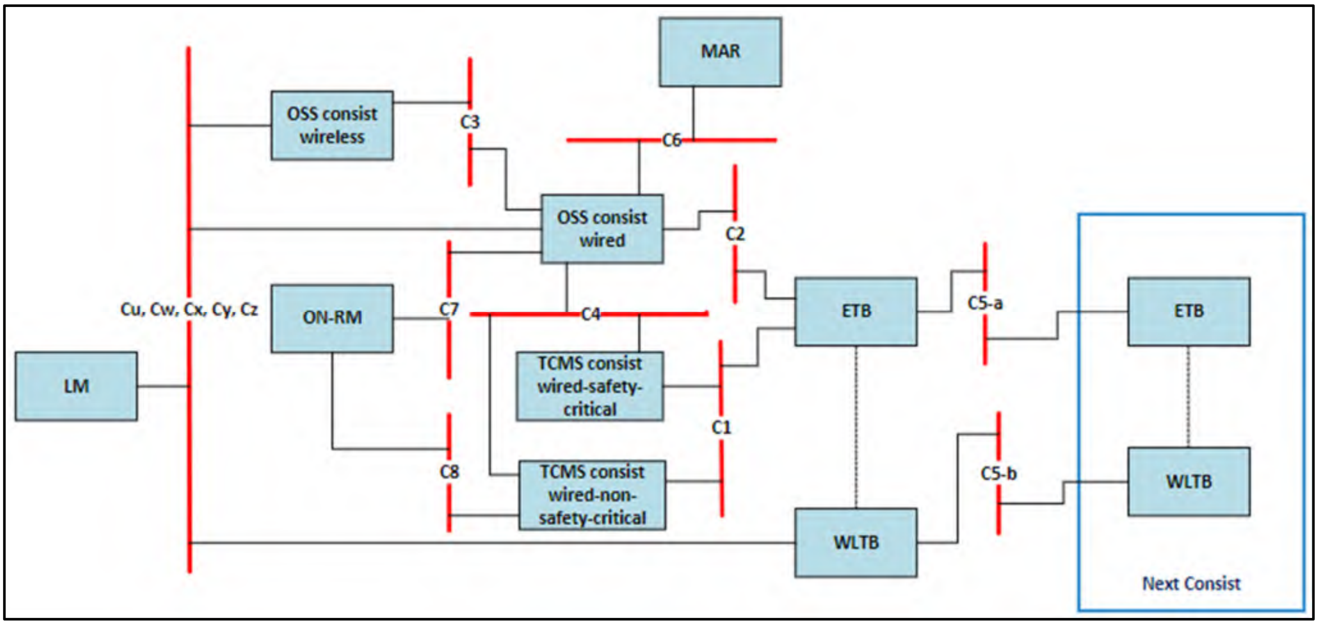


Figure 6-5: NG-TCN Conduits & Zones.

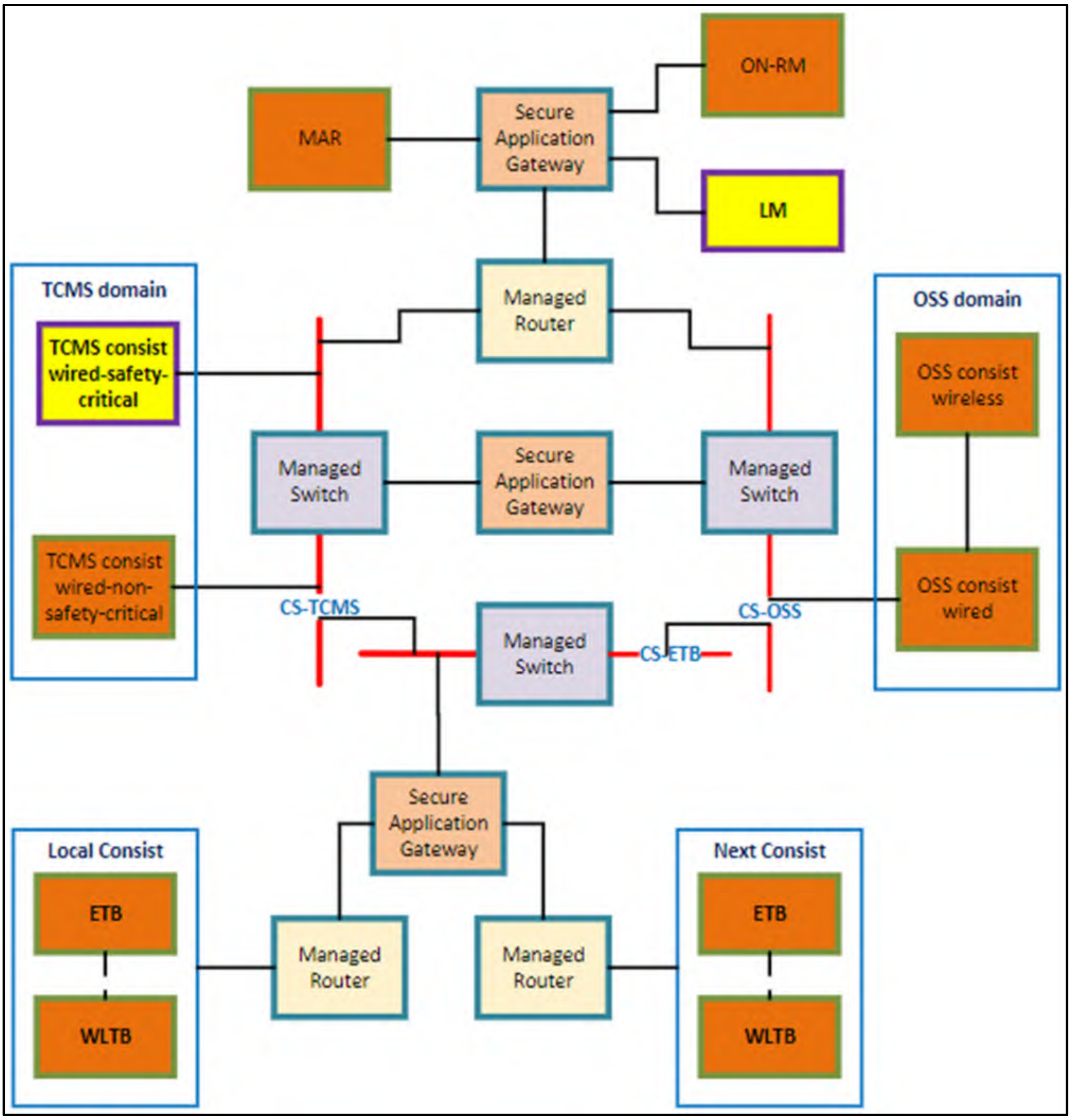


Figure 6-6: NG-TCN Conduits & Zones.

## 6.7 Risk Assessment Methodology for NG-TCMS and ATO

In the course of 2022, a risk assessment methodology has been developed, fully aligned with ISA/IEC 62443 series of standards, as well as with CL TS 50701 [2]. Furthermore, an excel tool has been developed that implements this methodology.

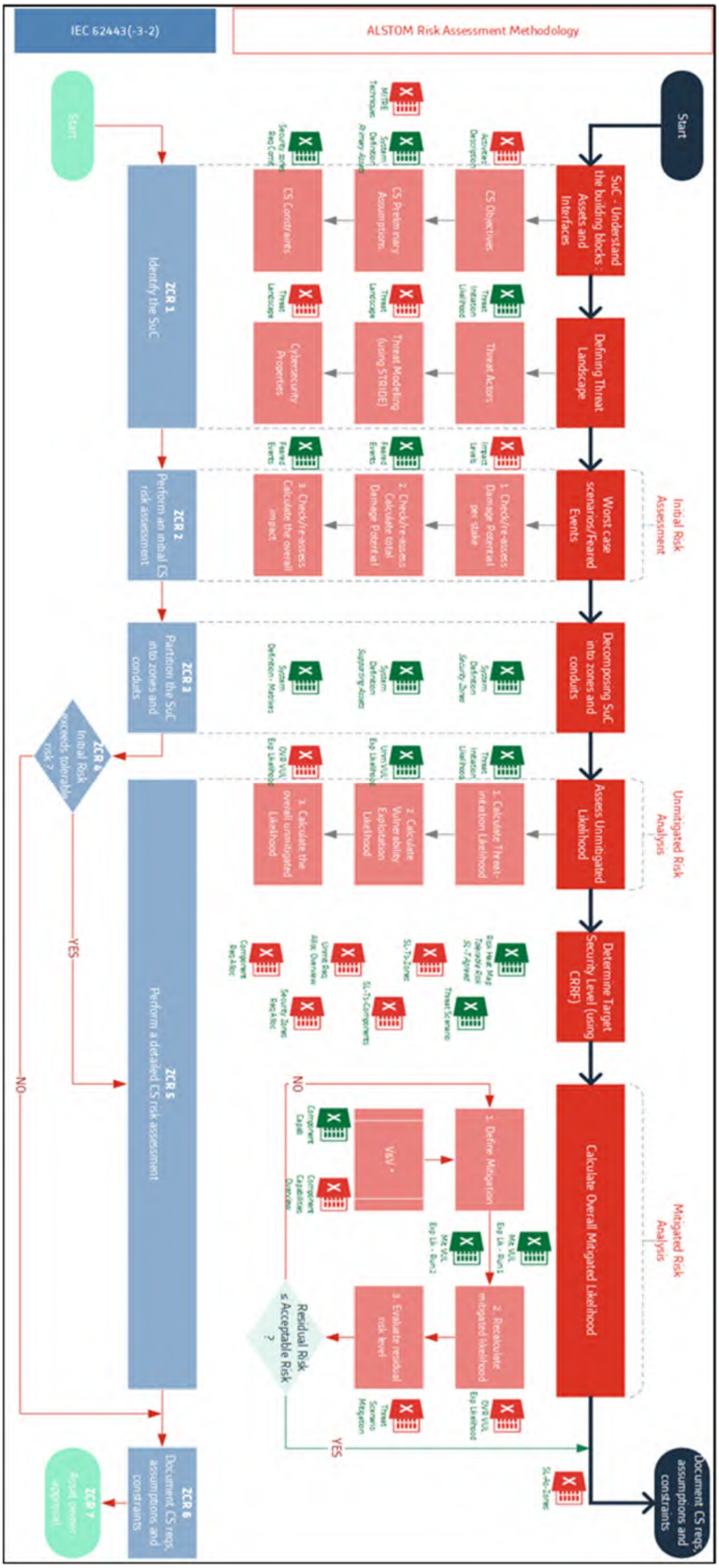


Figure 6-7: Methodology for NG-TCMS and ATO.

One of the key challenges that had to be addressed was to introduce in the scope of the methodology the management of attack paths (as part of the collaboration with the S2R TCMS activity, via the project CONNECTA-3), as well as to improve the impact and likelihood criteria defined in the previous Simplified Risk Assessment methodology [21], to match with the NG-TCMS environment. For both TDs (ATO, TCMS), special attention has been given to the management of Safety functions with respect to cybersecurity attacks, which was not covered by the previous analysis [14] [15] [16] [18].

- **System Under Consideration (SuC)**: This identifies the boundaries of the system to be assessed. The cybersecurity controls part of the project will be designed and implemented based on the results of the assessment within the context of the project.

To perform Risk assessment, we mainly require the Primary assets & Supporting assets, according to ISO 27001 [8] to get the System under Consideration and Zones & Conduits.

- **Primary & Supporting Assets**: Several core functions performed by the System under Consideration (SuC) can achieve the objective(s) of this system or subsystem, which will be referred to as primary assets. As primary assets require certain components to function in order to form the corresponding secondary assets, these components will further be referred to as supporting assets.
- **System under Consideration**: In a cybersecurity risk assessment, a SuC identifies the boundaries of the system that will be assessed. Using the results of the assessment, the design and implementation of the cybersecurity controls part of the project will be guided by the scope defined within the context of the project.

The above estimated assets are used to calculate the risk and find the ways to mitigate them.

**Security Zones & Conduits [4]:**

- **Zones**: As stated in the IEC 62443 standard, the generic guidelines for partitioning into zones are not sufficient to propose a consistent zone and conduit model: the result of the HLRA should be used to divide the system under consideration (SuC) into consistent zones in term of risks. Once the partition into zones is completed, the conduits are defined by gathering the communication channels between the same zones.
- **Conduits**: The ISA/IEC 62443 3-2 standard [5] provides rules for the partition into zones, the conduits being a logical grouping of communication channels that share common security requirement and that connect two or more zones.

**Impact Criteria:**

The impact of a risk event refers to its potential impact on the organization. Financial, reputational, regulatory, health, safety, security, environmental, employee, customer, and operational impacts may all be considered in impact assessments.

Table 6-2: Impact Criteria

| Impact Criticality Label | Severity Level | Safety | Operational/ Performance | Financial/ Reputation | Compliance |
|---|---|---|---|---|---|
| **Critical** | 4 | Life-threatening injuries (survival uncertain), fatal injuries and/or extreme damage to the environment | Train unusable, i.e., one or more fundamental functions are affected. The train usage is infeasible. | Existence-threatening financial damage and/or the incident will incur people suing the company, severe impact to the public image of the company | Extensive non-compliance to contracts, regulations and legislation with high penalties & liabilities (Personal liability with jail condemnation). Loss of license to operate. |
| **Major** | 3 | Severe and life-threatening injuries (survival probable) and/or large damage to the environment | Service required, i.e., an important function is affected. The train/vehicle can be used only with massive restrictions. | Substantial financial damage, but yet not existence-threatening and/or the incident may have a serious impact on the public image of the company | Restriction to operate. Major non-compliance to contracts, regulations and legislation with penalties & liabilities (Personal liability with jail conditional condemnation). |
| **Moderate** | 2 | Light and moderate injuries and/or minor damage to the environment | Comfort affected. The vehicle can be used with some restrictions. | Undesirable financial damage and/or the incident may have an impact on the public image of the company | Medium non-compliance to contracts, regulations and legislation with Low penalties & liabilities. (Personal liability with financial condemnation). |
| **Minor** | 1 | No injuries | No relevant effects, i.e., at most, an unimportant function is affected, and the train/vehicle can be used without restrictions. | No or tolerable financial damage | Minor non-compliance to contracts, regulations, and legislation with Low penalties & liabilities. |

Likelihood Calculation:

> Likelihood means the possibility of a potential risk occurring, interpreted using qualitative values such as low, medium, or high. This is in comparison with quantitative assessments, which use data and numbers. When using a quantitative assessment, you typically speak about Risk Probability and percentage.

Generally, The Likelihood calculation is done in three main steps:

1. Calculating for Single Threat Scenario.
2. Calculating for Single step in an Attack Path.
3. Calculating for the Complete Attack Path.

The attack paths for the different types of attackers (the list of attackers is aligned with ISO 27005 [9]) in the NG-TCMS along with the calculated likelihood by looking into the target exposure, are presented in the following diagrams. Steps in the attach paths are represented with logical AND and OR gates, according to the APTA methodology [1]:

Table 6-3: Likelihood of an Attacker

| | Hacker/ Cracker | Terrorist | Competitor | Goverment Organization | Hactivist | Criminal Organization | Script Kiddy | Layman | Insider |
|---|---|---|---|---|---|---|---|---|---|
| **CAP** | 3 | 3 | 3 | 4 | 3 | 4 | 2 | 1 | 3 |
| **INT** | 3 | 3 | 4 | 4 | 3 | 4 | 2 | 1 | 3 |
| **TARG** | 3 | 3 | 3 | 2 | 4 | 4 | 3 | 2 | 4 |

The complete list of attack paths in the NG-TCMS, is depicted in the following diagram, as part of the collaboration agreement between X2R-5 and CONNECTA-3 project [12].

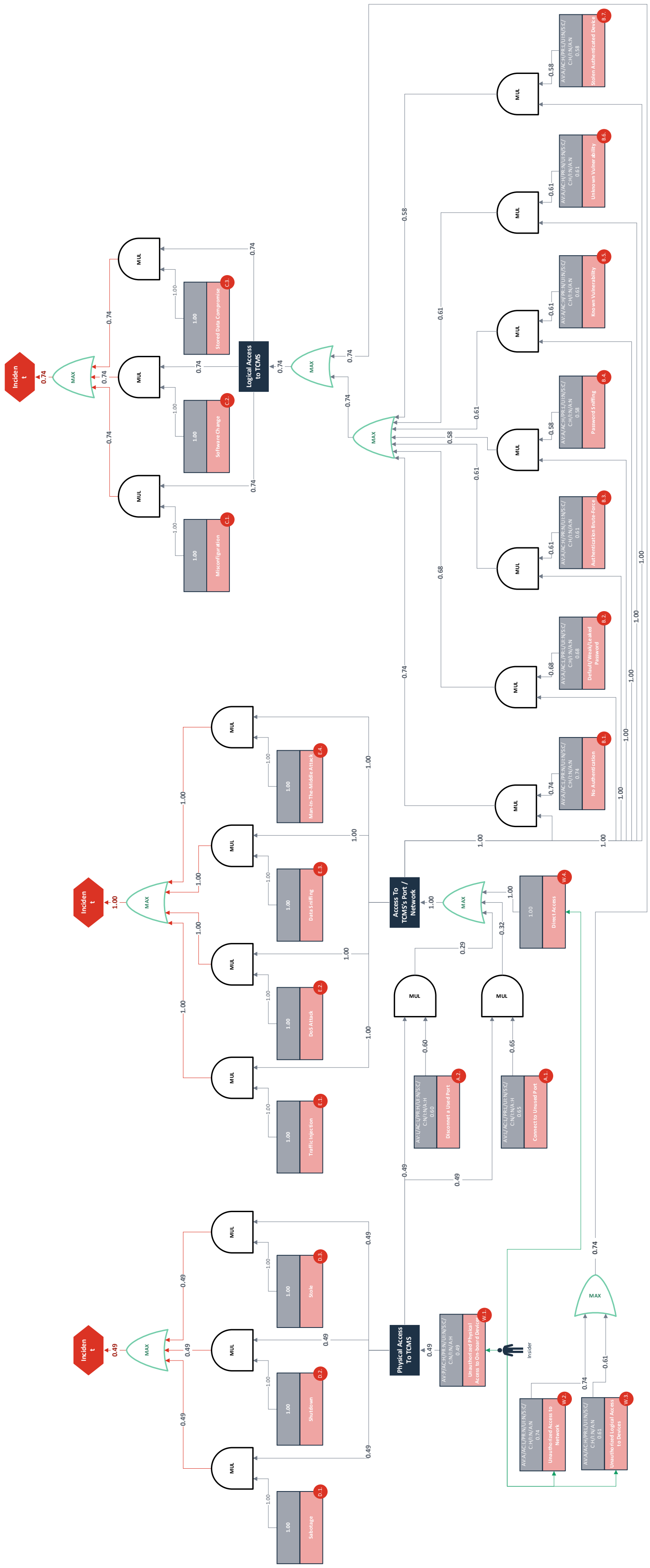

Figure 6-8: Attack paths from an Insider.

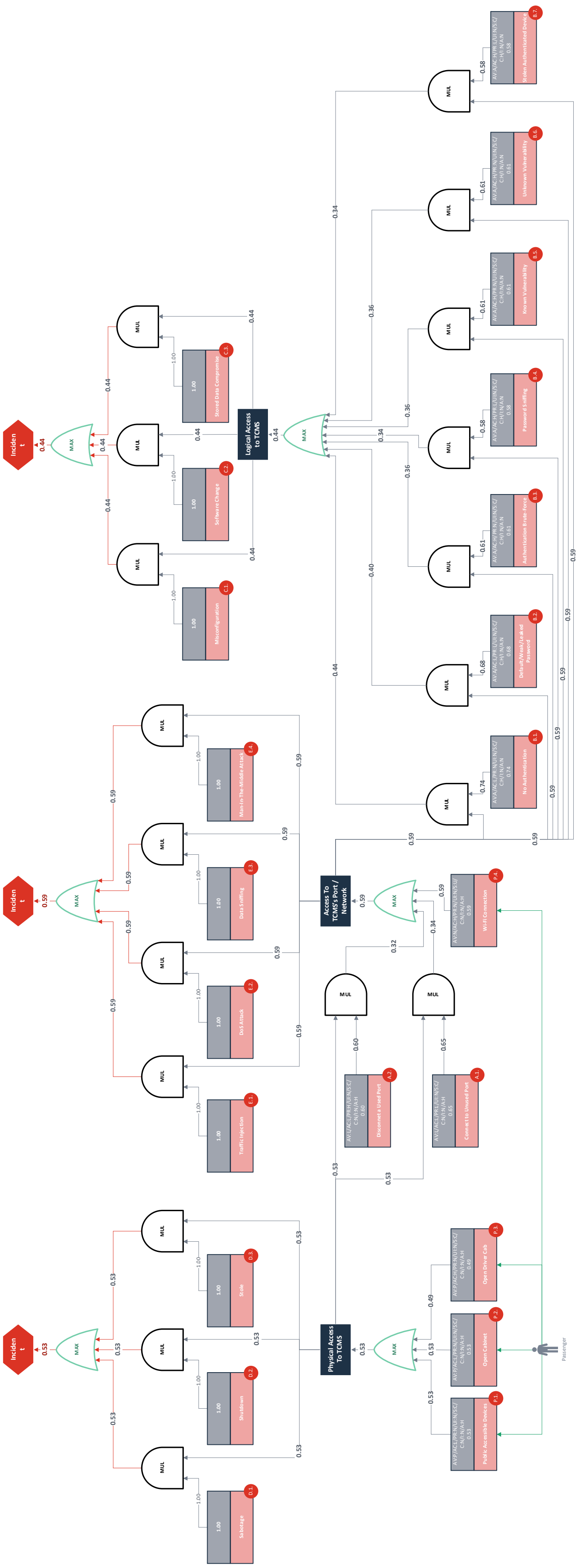

Figure 6-9: Attack paths from a Passenger.

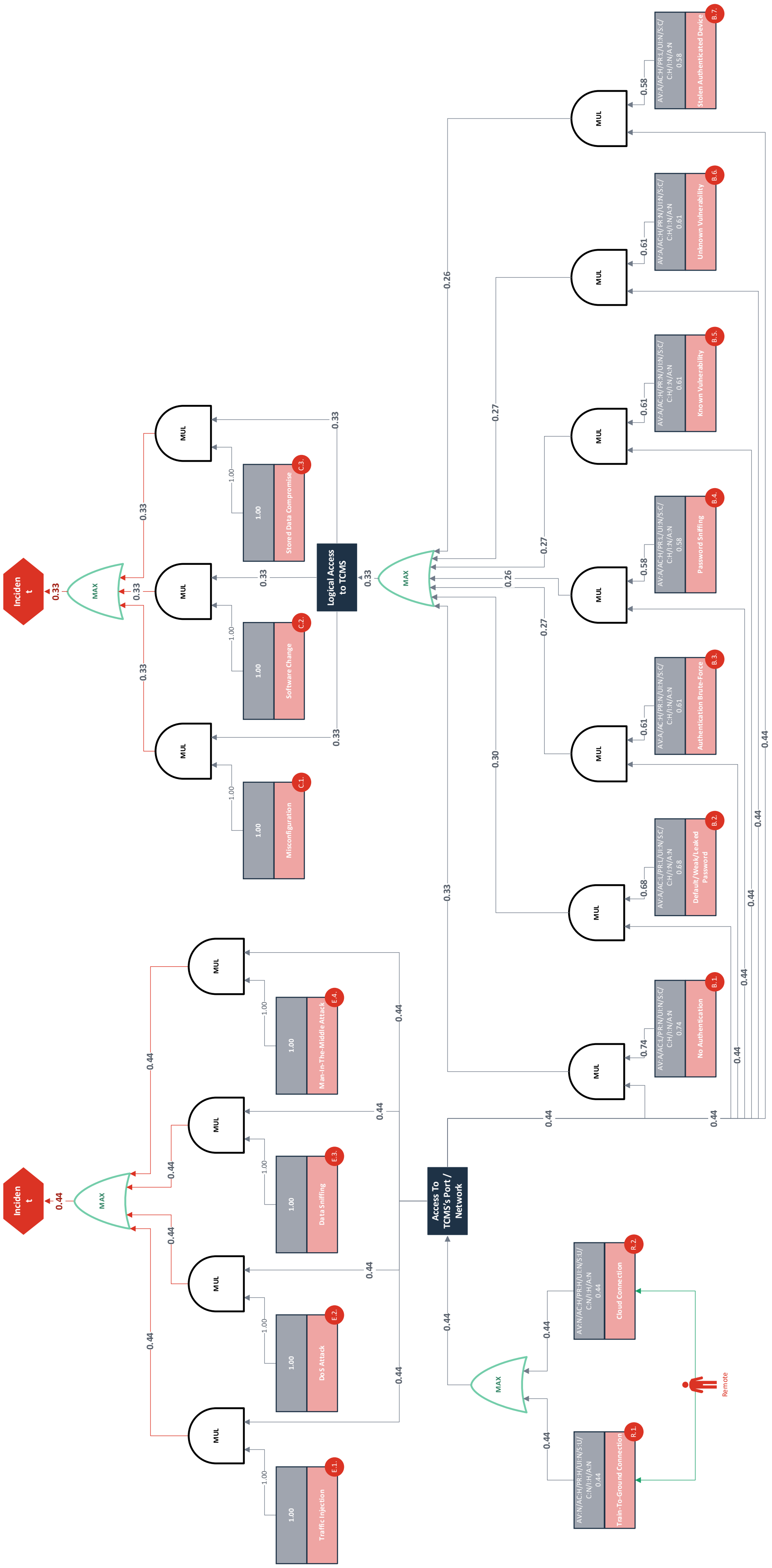


Figure 6-10: Attack paths from a Remote attacker.

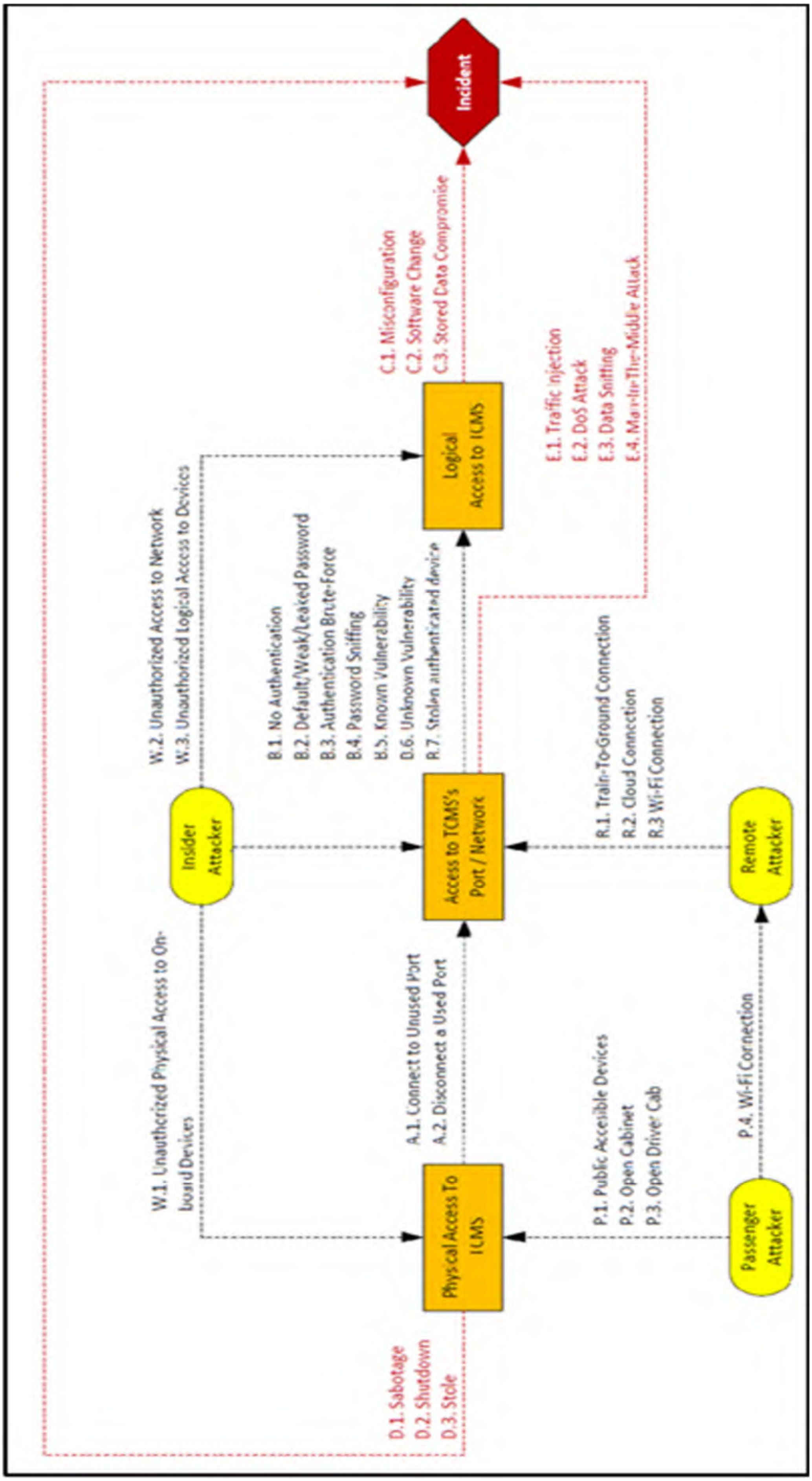


Figure 6-11: Attack paths in the NG-TCMS (@CONNECTA-3 group).

The Event Initiation Likelihood (i.e., the likelihood that an attacker will perform a successful attack) can be calculated as

$$EIL = \frac{(w_i * CAP + w_i * INT + w_i * TARG)}{\sum_{i=1}^{n} w_i}$$

Where wi are the weights assigned to adversarial threat actor's capability, intent and targeting. There can be different proposals for computing Average EIL: pessimistic, balanced and optimistic. The formulae for the balanced approach are as follows:

$$Balanced\ Max\ EIL_{per-threat-ID} = \frac{\sum_{i}^{k} w_i EIL_i}{\sum_{i=1}^{k} w_i}$$

$$Balanced\ Avg\ EIL_{per-threat-ID} = \frac{\sum_{i}^{k} w_i EIL_i}{\sum_{i=1}^{k} w_i}$$

$$Balanced\ Min\ EIL_{per-threat-ID} = \frac{\sum_{i}^{k} w_i EIL_i}{\sum_{i=1}^{k} w_i}$$

Table 6-4: Computing Pessimistic EIL values

| 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | Pessimistic |
|---|---|---|---|---|---|---|---|---|---|
| Hacker/Cracker | Terrorist | Competitor | Government Organization | Hactivist | Criminal Organization | Script Kiddy | Layman | Insider | |
| EIL | EIL | EIL | EIL | EIL | EIL | EIL | EIL | EIL | Max EIL |
| 3.00 | 3.00 | 3.43 | 3.14 | 3.43 | 4.00 | 2.43 | 1.43 | 3.43 | 4.00 |

Table 6-5: Likelihood criteria to initiate a certain threat event from a threat actor

| | Unlikely – 1 | Possible – 2 |
|---|---|---|
| **CAP - Capablility of the threat actor** | The attacker has limited resources, expertise and opportunities to support a successful attack. | The attacker has moderate resources, expertise and opportunities to support multiple successful attacks. |
| **INT - Intent of the threat actor** | The attacker actively seeks:<br>- to obtain critical or sensitive information;<br>- to disrupt the system's cyber resources;<br>The attacker does not concern about attack detection or disclosure. | The attacker seeks:<br>- to obtain or modify specific critical or sensitive information;<br>- to disrupt the system's cyber resources;<br>- to impede system functionalities<br>by establishing a foothold in the organization's IS/ICS.<br>The attacker is concerned about minimizing attack detection/disclosure, particularly over long time period attack. |
| **TARG - Targeting of the threat actor** | The attacker uses publicly available information:<br>to target a class of high-value railway vendors / companies / organizations.<br>by seeking:<br>- targets of opportunity of this class. | The attacker analyses publicly available information:<br>to target persistently specific high-value railway vendors / companies / organizations.<br>by focusing on:<br>- key position employees;<br>- programs;<br>- the system itself;<br>- information used by the system. |

| | Likely – 3 | Certain – 4 |
|---|---|---|
| **CAP - Capablility of the threat actor** | The attacker has a sophisticated level of expertise, with significant resources and opportunities to support multiple successful coordinated attacks. | The attacker has a very sophisticated level of expertise, is well-resourced and can generate opportunities to support multiple successful, continuous and coordinated attacks. |
| **INT - Intent of the threat actor** | The attacker seeks:<br>- to undermine or impede critical aspects of a core system function;<br>- to place itself in a position to do so in the future<br>by maintaining a presence in the system.<br>The attacker is very concerned about minimizing attack detection/disclosure, particularly while preparing for future attacks. | The attacker seeks:<br>- to undermine, severely impede, or destroy a core business function or component<br>by exploiting a presence in the system.<br>The attacker is concerned about disclosure only to the extent that it would impede its ability to complete stated goals. |
| **TARG - Targeting of the threat actor** | The attacker analyses information obtained via reconnaissance:<br>to target persistently a specific organization, enterprise, railway system or system function.<br>by focusing on:<br>- specific high value or mission critical information;<br>- resources;<br>- supply flows;<br>- system functions or specific employees supporting these functions;<br>- key position employees. | The attacker analyses information obtained via reconnaissance and attacks:<br>to target persistently a specific organization, enterprise, railway system or system function.<br>by focusing on:<br>- specific high value or mission critical information;<br>- resources;<br>- supply flows;<br>- key position employees;<br>- providers / suppliers;<br>- partner organizations. |

For pessimistic and optimistic strategies in calculating the likelihood for an attacker, we suggest considering the maximum and rounding lower nearest integer, respectively.

The probability of threat event successfully exploits a given vulnerability (or set of vulnerabilities) in the targeted environment and cause an adverse impact. It will be referred to as vulnerability severity (VS). The vulnerability severity (VS) calculations will be based on the Common Vulnerability Scoring System (CVSS) [9] [10]. The calculation of CVSS score is based on CVSS3.1. For each supporting asset, following vulnerability categories from threat landscape, a CVSS score is computed which contributes to likelihood calculation.

$$\text{Vulnerability Severity} = \begin{cases} 1, & \text{CVSS} < 4 \\ 2, & \text{CVSS} < 7 \\ 3, & \text{CVSS} < 9 \\ 4, & \text{CVSS} \leq 10 \end{cases}$$

$$\text{Overall Likelihood}_{\text{per-asset-ID}} = \left\lceil \frac{\text{VS} \times \text{EIL}}{4} \right\rceil$$

Where $\lceil \cdot \rceil$ represents rounding to next nearest integer.

$$\text{Risk} = \text{Impact} \times \text{Overall Likelihood}$$

A risk matrix is a useful tool for organizations to identify, assess, and prioritize risks in a structured and objective way, and to help make informed decisions about how to manage and mitigate those risks. Table 6-6 defines the severity classes for the risk level values t used for the cybersecurity risks assessment. The chosen risk matrix and appropriate rationale can be followed from Table 6-5 and Table 6-2 respectively.

Table 6-6: Risk Matrix

Risk Matrix : Risk = Likelihood x Impact

| Likelihood - L | | | | | |
|---|---|---|---|---|---|
| | 4: Certain | 4 Low Severity | 8 Medium Severity | 12 High Severity | 16 Very High Severity |
| | 3: Likely | 3 Very Low Severity | 6 Medium Severity | 9 Medium Severity | 12 High Severity |
| | 2: Possible | 2 Very Low severity | 4 Low Severity | 6 Medium Severity | 8 Medium Severity |
| | 1: Unlikely | 1 Very Low severity | 2 Very Low severity | 3 Very Low Severity | 4 Low Severity |
| | | 1: Minor | 2: Moderate | 3: Major | 4: Critical |
| | | Impact - I | | | |

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Disclaimer: This dissemination of results reflects only the authors' view and the Shift2Rail Joint Undertaking is not responsible for any use that may be made of the information it contains.

## 6.10 Authors

**Dimitris Sisiaridis** has a PhD in Cybersecurity and a Master in Computing Science. He's CISSP and ISA/IEC 62443 certified. He was an active Researcher in Big Data projects, developing self-learning engines for detecting frauds and threat in large-scale infrastructures utilizing machine learning and AI. Currently he is working as the Cybersecurity Coordination Leader for Mainline projects in Alstom.

E-Mail: dimitrios.sisiaridis@alstomgroup.com

**Sai Lokesh Posa** holds a Master's degree in Computer Security. He is ISO 27001 and CISCO certified. He has hands-on experience on OWASP Top 10 vulnerabilities and experienced in Cyber Threat Intelligence, which is detecting the Malicious websites and initiating the takedown. Currently, he is working as a Cybersecurity Engineer at IRT Railenium for the X2Rail-5 Project.

E-Mail: sai-lokesh.posa@railenium.eu

# 7 Functional test of EULYNX Components in RailSiTe® Laboratory

*Miriam Grünhäuser, Igor Bier, Katharina Hartmann, Lennart Asbach;*
*DLR, Institute of Transportation Systems, Braunschweig, Germany*

## 7.1 Introduction

EULYNX (European Initiative Linking Interlocking Subsystems) is a European initiative founded in 2014 to harmonize and standardize interfaces in rail infrastructure. First members of the initiative were railway operators DB Netz (Germany), Prorail (Netherlands), Infrabel (Belgium), SNCF (France), CFL (Luxembourg) and Network Rail (Great Britain). Operators from other countries have joined by 2020, so that currently the initiative includes 14 countries.

Based on the challenge that maintenance and further development of existing field components through the various interfaces and manufacturers is both - cost and time-consuming, the focus was on the development of uniform industrial standards for modular signal box technology. With this purpose, standardized architecture and interfaces were developed, for example for communication (SCI, Standard Communication Interface), for maintenance (SMI, Standard Maintenance Interface), for diagnosis (SDI, Standard Diagnostics Interface) and for the transfer of safety-critical information (SSI, Standard Security Interface). The IP-based communication between system components uses RaSTA (Rail Safe Transport Application) protocol, which is specially tailored to the requirements of railway signal technology [1].

From technical point of view, EULYNX relies on formal description languages as SysML and RailTopoModel for modeling stretching topologies. Development milestones in so called Baselines are tracked within the standardized EULYNX reference architecture in which functions and components of the system are described. The latest, published version is Baseline 3 [2], which will be used in Germany in several projects by Pintsch, Hitachi, Alstom and Thales. The earliest start of operating digital interlocking technology with Baseline 3 will be September 2023 in the city of Zwiesel in eastern Bavaria.

Especially in safety-critical environments like the railway sector testing of the used components and their communication is mandatory. Therefore, this paper describes the integration of the rather new EULYNX specifications into an existing testing environment for railway applications. First, the general motivation of laboratory tests is presented leading to additional requirements for testing against the EULYNX specification. After that follows the main part where the integration into the testing laboratory RailSiTe® (Railway Simulation and Testing) regarding the overall concept and software as well as hardware components is explained. Finally, we present current testing opportunities for suppliers and an outlook on further developments.

## 7.2 Motivation of laboratory tests

The Institute of Transportation Systems at the German Aerospace Center in Braunschweig, Germany is developing new test methods and concepts for railway management and signaling technology since its foundation in 2001. The institute's own developed test laboratory RailSiTe® has been accredited for testing ETCS components since 2012 according to DIN EN ISO / IEC 17025 [3]. Within 2023 accreditation will be extended to include testing for infrastructure components according to EULYNX specifications. The motivation is to transfer the increasing number of tests from the field to a controlled laboratory environment. Simulation environments, such as RailSiTe®, offer the advantage that they enable on the one hand cheaper and faster tests and on the other hand test constraints are precisely reproducible. In addition, testing of in particular newly developed components in the field is much more complex and cannot cover all scenarios to be tested (such as failures or defects) but were needed to approve them. Faster and more efficient tests are also possible in test laboratories since test cases are formalized and can be carried out automatically. To achieve compatibility and conformity an object controller is pre-switched before each infrastructure element. The interfaces of these object controllers are standardized. In order to demonstrate conformity of EULYNX requirements and the compatibility between individual components, extensive tests are also necessary here. In the RailSiTe® laboratory, these tests can be carried out independently - from manufacturer and operator - and efficiently.

## 7.3 EULYNX testing requirements

Driven by the need to standardize interfaces EULYNX working group is building up specifications for conformity tests. These specifications are the common base in case of requirements for testing all infrastructure elements such as signals, level crossings, points, and so on. The aim of EULYNX organization is that all specifications are complete, correct, approved and free of charge available. After building up all needed requirements they intend to convert to standardization body for EULYNX to set up a European standard, which includes the handling of bug fixes, error corrections and support national implementations.

Based on the specification the EULYNX working group provides formalized test cases, which consist of multiple test steps for testing the compliance against the specification and refer to one or more requirements. Foremost advantage of formalized test cases is that they are unequivocal and, thus, can be executed automatically. Another simplification for laboratory testing is the standardized catalog of requirements for laboratories. Therefore, the automation of test processes can be executed in real time [4].

The following image gives an overview of the architecture used in EULYNX. It shows which standardized interfaces are fixed for the individual infrastructure elements in the railway sector to communicate with each other and exchange data.

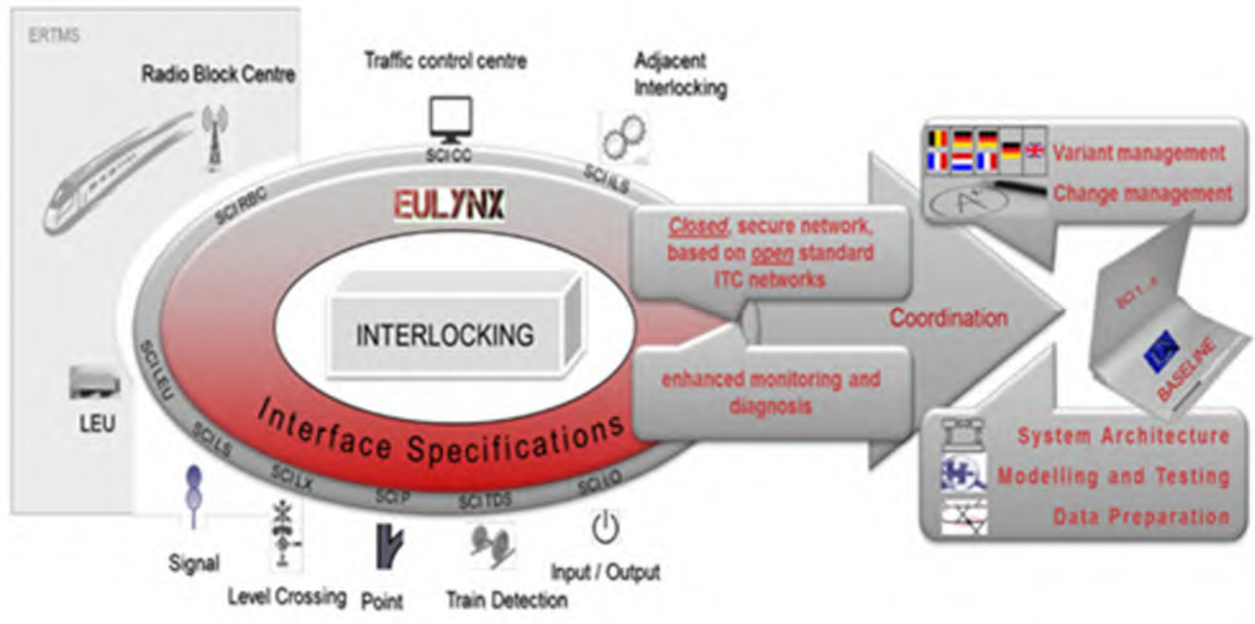


Figure 7-1: EULYNX architecture [5]

The architecture contents 10 different interface specifications summarizing different groups of infrastructure elements. The acronyms follow the rule: first SCI for "Standard Communication Interface" followed be the abbreviation for the particular infrastructure element such as LS (light signals), LX (level crossings), P (points), TDS (train detection system), I/O (input / output device) and TSS (trackside safety system). On top of theses groups there are common defined interfaces for radio block center (SCI RBC), traffic management system (SCI CC), adjacent interlocking (SCI ILS) and lineside electronic unit (SCI LEU) [10]. In the next part the interfaces currently implemented in the RailSiTe® laboratory will be described.

## 7.4 EULYNX Implementation

The RailSiTe® laboratory at the Institute of Transportation Systems is able to test railway infrastructure elements against conformity to the EULYNX specifications. For this purpose, it provides software to connect the standardized interface (SCI) to the laboratory environment, in which all other components can be simulated. The behavior of the interface of the DUT (Device under test; the Object Controller of the respective infrastructure element) is compared in individual test steps with the requirements of the EULYNX specifications. The result of this test is a report including the evaluation "specification is met" (passed) or "specification is not met" (failed) for each individual test step. This test report is provided to the customer for approval.

## 7.5 Test concept

The laboratory offers conformity and interoperability testing of individual infrastructure elements such as level crossings, switches, traffic signals, etc. Each DUT has a preceding object controller which communicates with the simulated elements in the RailSiTe® testing software via the corresponding interface. The associated object controllers are connected via LAN to the laboratory software and are integrated into the simulation environment. On the software side, our test program is used for this purpose. The object controller exchanges - either with the interlocking or with other infrastructure elements - formalized messages (e.g. a connection request in RaSTA or a SCI command or message). This is followed by a check whether the object controller reacts according to the test case. The result is output as a target / actual comparison in the form of a test report.

### 7.5.1 Test execution

In the first step, customer's hardware (object controller) is connected to the laboratory via ethernet. Then the individual customer-specific parameters are adjusted in the configuration file. After successful integration, the test sequences (multiple test cases that are executed after another) are started and run completely automated. If differences between the expected messages and received messages are detected, the test steps are marked as failed and the sequence can continue or stop, depending on the settings. All formalized steps are automatically evaluated and marked in the test report as passed or failed.

### 7.5.2 Evaluation of the test results

The automated comparison and evaluation of the requirements from the EULYNX specifications (in the formalized test cases) and the actual state of the DUT already takes place during the test run. This evaluation output is displayed in a report where the test results are unambiguous (passed / failed) and are completely traceable due to the formalization of the test cases. The test report is generated automatically and serves the manufacturer as proof of the conformity of his component.

### 7.5.3 RailSiTe® - Test Bench Implementation

**Hardware**

The mobile EULYNX test bench (Figure 7-2) is a highly mobile and compact "test lab on wheels", which can be set up at any manufacturer and can also be controlled remotely, if needed.

**KVM-Switch**: The work place is equipped with a Full-HD display and a keyboard with touchpad (like a laptop). It is possible to connect and switch between 7 video inputs.

**Ethernet-Switch**: Ethernet-Hub can be used to test multiple devices at once and offers the possibility to work in a virtual private network (VPN). It enables remote testing and better support through DLR in case of problems.

**Raspberry Pi**: It works as an object controller simulator (Light Signal in this case). Multiple LEDs can be controlled via WAGO-Box for testing and implementation purposes.

**WAGO Modbus Module**: The Modbus-Protocol is a communication protocol based on a Master/Slave-Architecture. The protocol's goal is to establish a quick, reliable and fast communication between the automation system and field elements. The WAGO-Modbus provides digital I/O's that are used in simulation of error signals (e.g. faulty Light Signal) for object controllers.

**PC**: The operating system is Ubuntu 22.04 LTS. The PC has multiple Ethernet Ports, a wireless network interface controller, a 256 GB SSD Card containing the OS with two extra 2 TB RAID hard drives. As a consequence, this redundant setup can ensure continuous workflow even in case the SSD or one of the hard drives' crashes.


Figure 7-2: The mobile EULYNX Test Bench (Photos: DLR)

**Power Supply**: The power supply has two channels (Master/Slave) with voltages of +/- 0-30 V (or +/- 0-60 V) and can generate a current of 0-10 A. This covers the needs of typical railway applications (48 V) and different train components can be supplied with voltage and therefore be automatically tested.

## Software

The architecture of the RailSiTe® testing software is shown in Figure 7-3 and each module will be explained in this chapter.

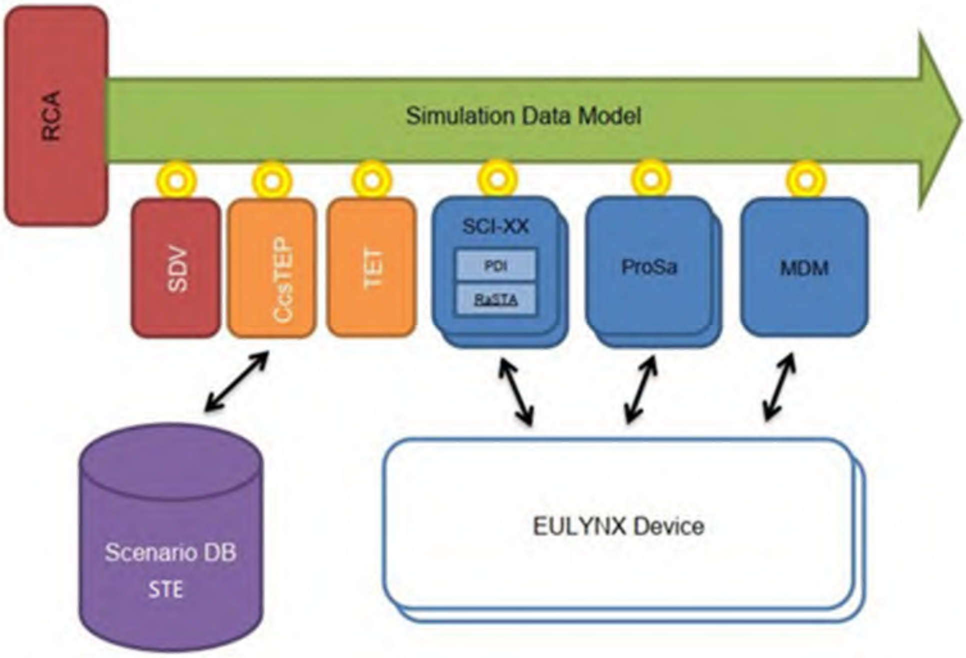


Figure 7-3: Architecture of the RailSiTe® Test Software

The EULYNX test sequences and cases are stored in the Scenario Database (DB) and can be easily imported to or exported from the DB in its original Excel format. The Test Editor (STE) manages the Scenario DB and allows to edit existing test sequences as well as generating new ones (Figure 7-4).

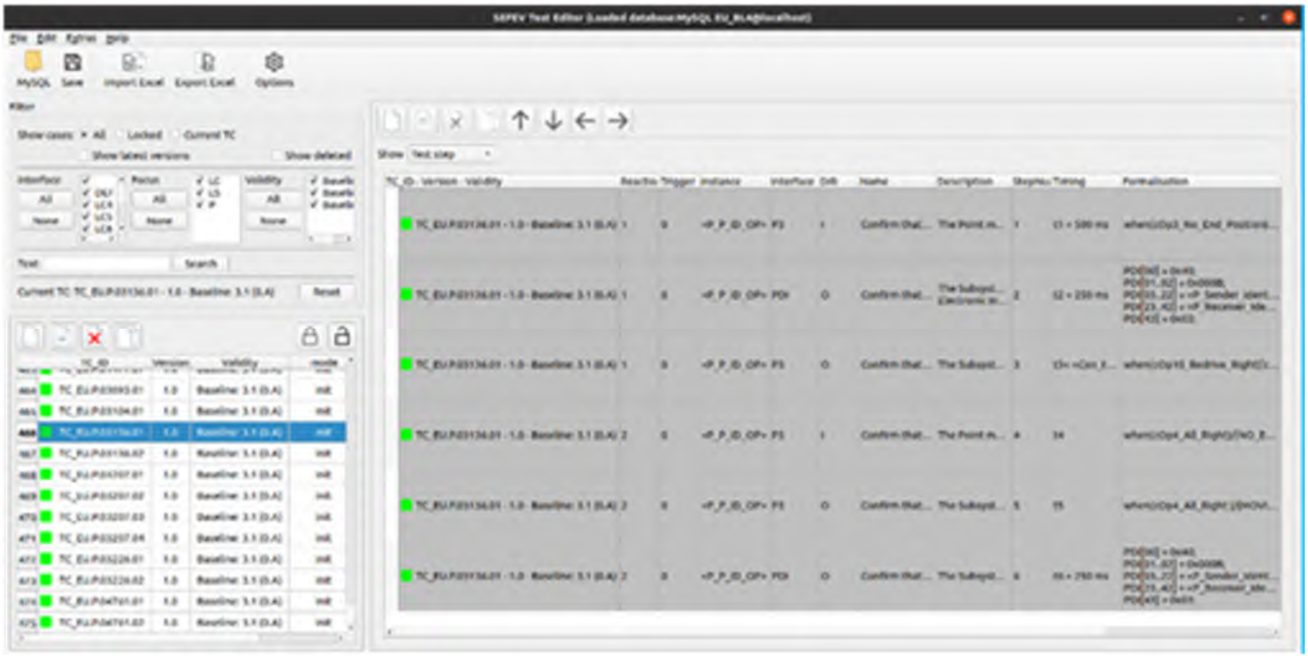

Figure 7-4: Scenario DB - An EULYNX Database with published test cases and self-build scenarios / sequences with multiple (sub) test cases (Screenshot: DLR)

The RailSiTe® Control Authority (RCA) starts and configures each component and coordinates the construction of the simulation data model which makes it the central application for running tests. All configuration parameters and further settings (e.g. RaSTA, ports, IPs) that are needed are stored in an individual file that is unique for each test sequence. Based on the configuration file the RCA starts all necessary simulation components and establishes a network connection to them. During the simulation, the RCA monitors and controls the components and synchronizes the distributed simulation data model.

The Simulation Data Viewer (SDV) offers a real-time view of the contents of the simulation data model.

The laboratory modules CCS Test Event Player (CcsTEP) and Test Event Tracker (TET) control the processing and logging of test scenarios. The TET logs scenario events, technical messages and models transitions to an SQLite or MySQL database. The CcsTEP first creates an event list by reading from the scenario database. During the simulation, these events are sent to the specified interfaces in the defined order indicated in the event list.

The laboratory modules Standard Communication Interface (SCI), Maintenance and Data Management (MDM) and Probe and Saboteur (ProSa) connect the DUT to the laboratory software.

The Maintenance and Diagnostic Module (MDM) is the interface between all connected test devices and the simulation environment for performing maintenance and diagnostic tasks. Currently, it is limited to receiving and logging SNMP (Simple Network Management Protocol) messages within the TET.

The ProSa-module connects the DUT to the simulation environment. By using this module, it is possible to receive test steps representing a sabotage event from CcsTEP and send them to the DUT or to receive probes from the DUT (Figure 7-5). Alternatively, both events can be invoked manually. The connection between a module in the simulation environment and the DUT is realized by WAGO modules.

## 7.6 Conclusion and Perspective

The implementation of the initial set of EULYNX tests into the laboratory has been completed. It was possible to integrate the elements under test into the simulation environment of the lab so that according to specifications the interfaces can be tested. At the present time, only a few specifications for some infrastructure elements are published. Therefore, in the coming months, continuous integration of new specifications has to be done as suppliers will have the need for testing their newly developed infrastructure elements for conformity.

Since tests are running in the RailSiTe® laboratory, next step is to bring the lab to the system to be tested. During the conception of EULYNX test laboratory the possibility of transporting the lab to the system to be tested has already been considered. The housing is fitted with rolls and has handles on both sides so that it can be brought to the customer’s lab or anywhere in the field. Environmental conditions such as temperature and weather protection must be maintained. For executing these remote tests, the laboratory can be accessed via VPN (virtual private network) by an employee of the DLR in the institute of transportation systems.

In conclusion, EULYNX tests are brought to the lab and are successfully implemented for part of the published specifications. Suppliers can get a test report including the statement whether the interfaces conform to specifications.

In the next step it is planned to widen the tests to more supplier and other infrastructure elements.

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## 7.8 Acknowledgments

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## 7.9 Authors

**Miriam Grünhäuser** is research scientist with 5 years of experience in rail, testing and accreditation topics at DLR Institute of Transportation Systems. Beyond that, she is working as project manager for different research projects. Before that her work was focused on different controlling topics. Miriam holds a degree in industrial engineer.

E-Mail: Miriam.Gruenhaeuser@dlr.de

**Igor Bier** has been a technical employee (B.Eng.) at the DLR Institute of Transportation Systems since 2020 and has gathered experience in topics like test automation, rail hardware integration and remote-control operation. A part of his work was the integration of EULYNX in the environment of the RailSiTe® Laboratory. His previous experiences are in automotive testing and acoustics.

E-Mail: Igor.Bier@dlr.de

**Katharina Hartmann** has been a research associate at the DLR Institute of Transportation Systems since 2020. Her work focuses on testing components for rail and automotive communications as well as project management. Katharina holds a degree in computer science and is currently deepening her knowledge in technology-oriented management with a focus on service design for digital products.

E-Mail: Katharina.Hartmann@dlr.de

**Lennart Asbach** heads the Verification and Validation Department at the Institute of Transportation Systems of the German Aerospace Center. After studying mechatronics at TU Dresden, he has been researching methods for simulation-based verification and validation of ground-based traffic systems since 2009. Until 2015, the focus was on the railroad system, in particular the European Train Control System ETCS; subsequently, the focus of the research work was extended to automated and connected driving on roads. Lennart Asbach is head of the accredited test laboratory RailSiTe® and one of the central contacts for the Test Bed Lower Saxony.

# 8 Autonomous Train AI-based Systems : Datasets Domain Adaptation

*Ankur Mahtani; IRT RAILENIUM, Famars, France*

## 8.1 Introduction on data insufficiency

Work package 1 of EU-funded TAURO project (Technologies for the Autonomous Rail Operation) aims to study data types correlation for multisensorial systems with synthetic data. This study is based on the TAURO delivery [10].

Data insufficiency is the most common problem occurred in modern AI. The available datasets are too small or, even while data are readily available, the sheer size of unlabeled data makes manual labeling infeasible. Especially for object detection and semantic segmentation tasks, where labeling cost is prohibitively high and time consuming.

Synthetic data are an interesting pipeline to solve data insufficiency problem. The generated data are used to create novel and diverse training datasets, and more to augment the existing dataset to cover insufficiently represented data distribution. Moreover, synthetic data have been also used to solve the privacy problem. Since real data contains sensitive and private information that cannot be freely used. In spite of the efficiency of synthetic data to address data insufficiency problems, models trained on synthetic data fail to perform well as on real data. This mainly due to the domain gap between synthetic and real data. The purpose of this document is to describe different techniques used to correlate between data types (e.g. data domains) to efficiently leverage synthetic data to reach effective performances as on real databases.

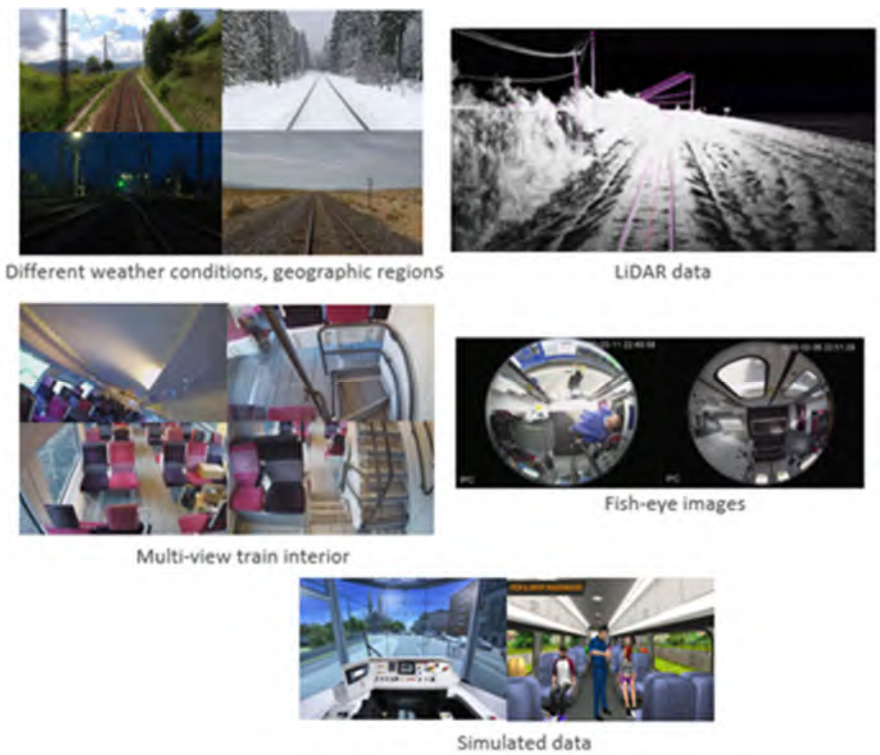


Figure 8-1: Examples of real-world data

## 8.2 Data types correlation

Various types of data are collected in autonomous train projects with several sensors, capturing the external and internal train environment. The collected data are stemmed from different sensors including camera sensors, laser sensors, odometry sensors and other industrial-ready sensors such as temperature measurement and pressure sensors. These large-scale collected data gather rich and diverse information of the train environment. Therefore, they are unlabeled and furthermore they may be submitted to GDPR data privacy policy. To create an efficient dataset for data-driven AI models, the dataset must be diverse covering various conditions and scenarios (weather conditions, geographic regions, and different scenes / objects appearances, and many more). Synthetic data are a promising technique to address various data problems including data availability, cost reduction, security, or privacy concerns. It is an inexpensive alternative to real-world data to train AI models. Synthetic datasets are automatically labelled data and can model any domain and include rare and complex scenarios, particularly infeasible or dangerous real-life events. These artificial data are generated with properties close to real data using diverse rules, statistical models, simulations or other techniques. Several synthetic datasets have been composed in the recent years; the main purpose is to generate synthetic datasets reflecting the real-life data. In [1] authors give an overview of various existing synthetic datasets, including synthetic people, indoor / outdoor environments, etc. Moreover, the authors outline direction to further improve synthetic data, making it more useful for a wide variety of applications in computer vision and other fields. Recent progress in machine learning propose a variety of deep network models to learn a wide range of data types. Variational Autoencoders [2] and Generative Adversarial Networks [3] are two commonly used techniques in the field of synthetic data generation. Synthetic data can be used as a large dataset for transfer learning or even to train a neural network from scratch. However, models trained on the synthetic data fail to perform well on real datasets owing to the domain gap, known as the domain shift problem. The trained models learn latent feature distributions of the synthetic training data. The resulting network provides poor performance in the real dataset, since the generated synthetic data does not properly reflect the feature distribution of the target real domain. In fact, synthetic data only replicate specific properties of the real data. Whereas these latter gather higher variation in features, lighting, colour, etc. than simulated data.

Domain shift problem is encountered not only on synthetic-to-real context, but it can be found in other contexts such as weather changing conditions, geographic regions change, shift between different sensors, etc. Domain adaptation (DA) or domain transfer is a class of techniques to solve the domain shift problem. It aims to minimize the domain gap and to transfer knowledge between domains to mitigate the effect of performance drops.


Figure 8-2: Domain adaptation by transfer learning

## 8.3 Domain adaptation scenarios

Domain adaptation (DA) is a particular case of transfer learning [6]. The main objective of domain adaptation is to improve the performance of a model on a target domain containing any label or insufficient labelled data using the knowledge gained from a rich labeled source domain. Transfer learning can handle the shift problem between different tasks and different domains, while domain adaptation deals only with domains differences on a given predefined task.

Domain adaptation has been extensively studied in recent years, proposing various adaptation solution to different tasks such as computer vision problems, including semantic segmentation and object detection. DA has been also studied to solve domain discrepancy issues in natural language processing and signal processing fields.

Table 8-1: Domain Adaptation Scenarios

| Scenario | Description |
|---|---|
| **Synthetic to real adaptation** | Despite recent advancements in computer graphics and photo-realistic technologies, synthetic generated data are not sufficiently illustrating the real-world real-life data, which result in severe performance degradation. This adaptation scenario aims to reduce the domain gap between the synthetic and real data. |
| **Cross-camera adaptation** | Domain gap can be induced using different intrinsic and extrinsic camera properties like resolution, distortion, orientation, location. Hence, the captured objects will have different appearance, scale, and viewing angle. This can significantly reduce the model performance. |
| **Weather conditions adaptation** | Changes in weather condition can drastically decrease model accuracy when it trained on clean weather data. In fact, weather conditions introduce artifacts on data which can negatively impact the performances. |
| **Geographic location change adaptation** | Changes in geographical and environmental location may negatively impact the performance. Since similar objects may be different from one region to another. |
| **Source free adaptation** | Due to privacy concerns or legal issues, the source domain may not be available. Only the source trained model is available to perform domain adaptation. |
| **Multi domain adaptation** | A practical scenario is to adapt multi available source domain to a target domain. This is a challenging DA scenario which involves adapting the target distribution to all source sub-distributions. |

## 8.4 Domain adaptation techniques

Depending on the type of available target data (i.e. labeled or unlabeled), domain adaptation techniques can be classified into three classes [6] :

- Semi-supervised domain adaptation: The source domain is fully labeled, and only a subset of the target domain is annotated.
- Weakly-Supervised domain adaptation: The source domain is fully labeled, and the target domain is weakly annotated (i.e. presence or absence of object in case of object detection).
- Unsupervised domain adaptation: The source domain is fully labeled, and the target domain is completely unlabeled.

Unsupervised domain adaption is the most common and challenging domain adaption setting. It can be adopted to address the semi-supervised and weakly-supervised domain adaptation settings. Therefore, we focus in following on reviewing the main recent works on unsupervised domain adaptation. Particularly, we review techniques used to solve domain shift problem in the context of computer vision problem including object detection and semantic segmentation such as adversarial feature learning, pseudo-label based self-training, image-to-image translation, domain randomization, mean-teacher training, or graph reasoning.

## 8.5 Example of image-based Domain Adaptation

Object detection task is a computer technology related to computer vision and image processing. It aims to identify instances in images and video sequences. The object detection usually involves two main tasks:

- bounding box localization;
- bounding-box category prediction.

Creating a large-scale diverse object detection-based dataset is prohibitively costly and time consuming. It requires drawing bounding box for each instance and define its class category. According to [7], it may take a minimum of 35 seconds for labelling person instance of a typical urban road scene. Domain adaptation is a solution to reduce labelling cost problem, by transferring the knowledge acquired in diverse and rich labelled domains to a target unlabeled domain.

Different strategies have been used in the literature to address the problem of domain adaptation for the task of object detection [10].

## 8.6 Training a Deep Learning model using real and synthetic dataset

Experiments performed by mixing real and synthetic data has shown that:

- Mixing synthetic and real data increased the performance of neural network;
- Number of samples of synthetic data must be much higher than real data;
  - Real images have a higher variation in features, lighting, colour etc. than simulated data
- Synthetic background classes such as sky, road and vegetation containing large image areas might be sufficient for semantic segmentation task;
- Synthetic foreground classes such as luggage, passengers and bicycles have realistic shape, but poor texture can be more useful for object detection task.

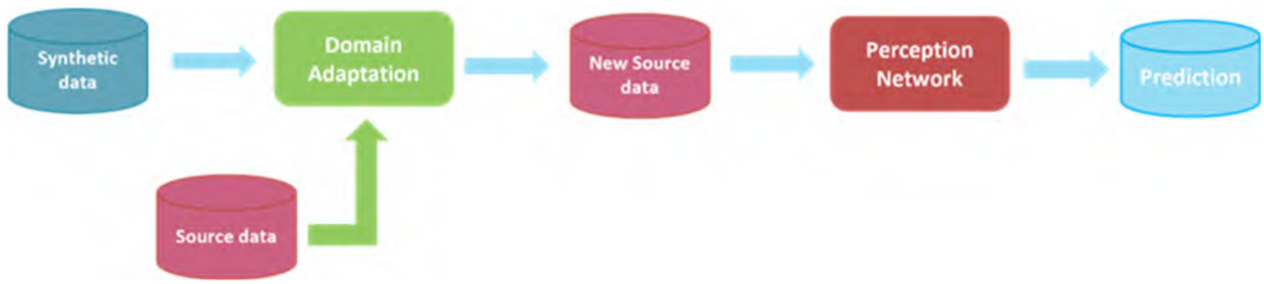


Figure 8-3: Training scenario using real and synthetic dataset

## 8.7 Perspectives

Deep Learning domain adaptation allows us to transfer the knowledge learned by a particular network on a source task to a new related target task. It has been successfully applied in tasks such as image classification or style transfer. In some sense, deep domain adaptation enables us to get closer to human-level performance in terms of the amount of training data required for a particular new computer vision task. Therefore, progress in this area will be crucial to the entire field of Computer Vision and it will eventually lead to effective and simple knowledge reuse across visual tasks in the railway sector.

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## 8.10 Authors

**Ankur Mahtani** is a Research Engineer in Artificial Intelligence at the Technological Research Institute Railenium. He earned his M.S. in Robotics Engineering at the Polytech Sorbonne school of France and his M.S. in Artificial Intelligence at the University of Québec of Montréal, Canada in 2019. He joined several projects on AI for autonomous systems in the railway sector such as the french Autonomous Train program in 2019. He is now the Deputy-Head of the AI Division of Railenium.

E-Mail: ankur.mahtani@railenium.eu

# 9 Specification of the AI based perception module for autonomous trains

*Insaf Sassi, Abderraouf Boussif; IRT RAILENIUM, Famars, France*

## 9.1 Introduction

The deployment of autonomous trains, in open environment, raises many questions and challenges, particularly those concerning the level of safety (globally at least equivalent to the level of the existing system with a human operator) and the means to be implemented to achieve it. An autonomous system is a system capable of making its own decisions to respond to all cases without human intervention (in an open and uncontrolled environment). It is therefore necessary to manage the functions of environmental perception, decision-making, planning and control, which have until now been largely allocated to the human operator.

According to [1], two functionalities are combined to enable the autonomous system to build for itself a useful representation of the state of the external (and internal) environment: Perception and reflection.

Besides, the general control architecture of an automated/autonomous system is divided into three subsystems or units (as depicted in Figure 9-1) with strong interactions between them and the surrounding environment: *perception system, planning system, and control system*. Hereafter, a short description of each system [2].

**Environment** of the system can generally be split into two categories, with respect to the system border: the internal environment and the external one. Hence, the environmental perception refers to developing a contextual understanding of the environment, such as obstacle locations, detection of road signs/marking, and categorizing data by their semantic meaning.

- **The internal environment** is the lower-level physical (and virtual) infrastructure used by the system's agents and objects. It may include the computer/processor/memory, batteries and other power sources, the operating system, communication hardware and software, data-base management software, etc.
- **The external environment** of a system (often referred to simply as its environment), is the collection of all entities with which the system interacts (i.e., the surroundings). It may include other systems (with their objects and agents), stand-alone objects, and any other physical or virtual entities that may affect, or be affected by, the system's behavior, via, sensors and actuators, or in other ways.

**Planning** refers to the ability of the autonomous system to apply policies and make decisions to achieve higher order goals in response to the current circumstances, as part of the reflection functionality. This is achieved by combining the processed information about the environment (perceived view of the real world) with established policies, domain knowledge and learning regarding how to respond to the presented environment. This leads to the autonomous decision.

**Control** refers to the system's ability to execute the previously planned actions that have been generated by the higher-level processes.

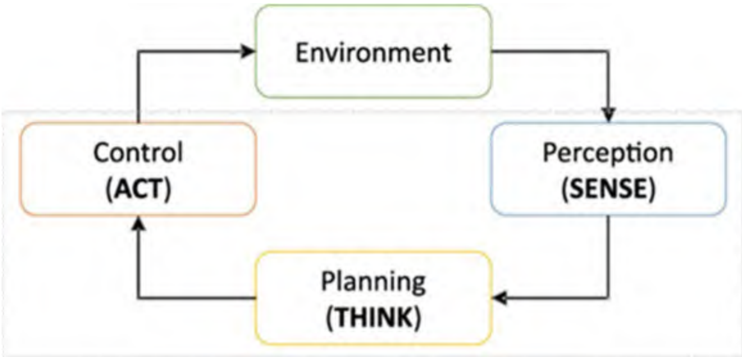


Figure 9-1: Perception-planning-control scheme.

**Perception** refers to how and how well the autonomous system understands the captured raw environmental data and is able to process its contained information into meaningful interpretations. The objective is to establish a sufficiently accurate view of the real world appropriate to the function of the autonomous system (e.g., discern the difference between an animal and a person, discern the difference between a track worker and a trespasser etc.). Generally, this task consists of environment perception and localization.

In the present paper, we will focus on the identification of perception tasks that an autonomous train of Grade of Automation (GoA) 4 needs to perform. A methodology of identification of AI perception functions is given in the sequel. This methodology is stipulated in task 1.2 of the project *Technologies for the Autonomous Rail Operation (TAURO)* to identify the list of functions that require implementing the artificial intelligence techniques. This task's objective consists in defining a proposal for certification methodology of safe functions based on artificial sense [3], particularly the perceptions functions.

## 9.2 Perception task in autonomous train

In the recent progress towards autonomous trains, and similarly to the case of autonomous cars, the autonomous driving components (ADS, ADAS, or ATO) basically provide the so-called perception layer or unit (sometimes including sensor fusion). These components implement artificial intelligence (AI) modules for the assessment of events and their relevance around the system, i.e., to provide the situational awareness. The use of such AI modules aims to help recognizing the environment and build a reliable and trustworthy environment model usable for complex automation tasks.

Figure 9-2 illustrates the control process for autonomous train. Like any autonomous system, it consists of three subsystems or unit, which are: perception unit, decision/planning unit, and control unit.

The perception unit contains:

- **The sensor unit**, which contains all the physical sensor devices that are used to capture and collect information and signals from the external or internal environment.
- **The monitor unit**, which contains the set of perception functions that are used perform the perception tasks, i.e., detection, recognition, classification, etc.
- **Positioning and map unit**, which provides the localization and mapping for the perception unit.

In fact, these three units build together a complete understanding of the environment and provide situational awareness for the autonomous train.

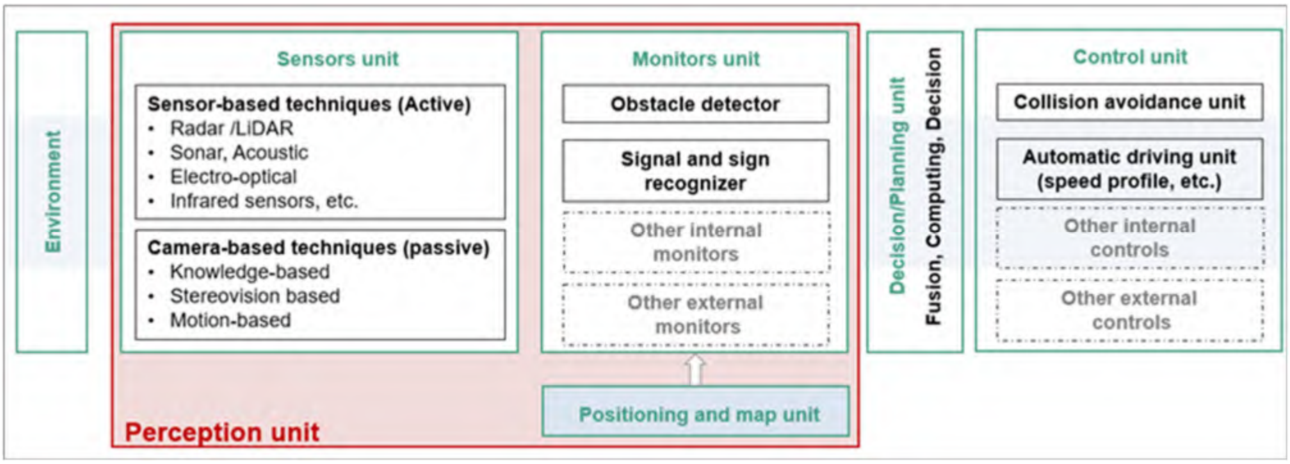


Figure 9-2: Perception-planning-control scheme for autonomous trains[4].

Our objective here consists in determining the perception functions belonging to the monitors unit, with an exhaustive identification of the required perception tasks to be performed.

## 9.3 Methodology of AI perception functions' identification

In order to identify the AI perception functions to be embedded and used by the autonomous trains, we firstly need to identify the perception functions currently performed within conventional trains (i.e., with a human driver and driving staff). Obviously, the majority of perception functions in conventional trains are assured by the human driver, relying on its human senses combined with its learned railway skills and knowledge.

The methodology we propose is conducted in two steps:

**Step 1: Identification of perception tasks**: it consists in gathering all perceptions tasks and activities which are performed by the train driver in order to ensure the safe operation of driving trains and the staff onboard.

**Step 2: Definition of the AI perception functions**: it consists in classifying and transferring the train driver and driving staff tasks and activities into AI-based perception functions.

Hereafter, we provide more details regarding these steps.

### 9.3.1 Step 1: Identification of perception tasks

This step aims to identify the perception tasks and activities performed by the train driver during a train journey and the driving staff. These activities are identified through analyzing and reviewing various railway standards, technical reports, and research papers. In the following are listed, in a non-exhaustive way, the most significant resources used in this works:

- Railway standards (EN 15380, TSI, ERA reports, etc.).
- Driver’s handbooks (Rule Book, train driver manuals, etc.).
- Shift2Rail projects (SMART: Obstacle detection, etc.).
- Other national and international projects (MoDSafe project, etc.).
- Technical/scientific reports.
- Research papers ([5], [6])

A pre-analysis of the abovementioned documents (particularly Driver's Handbooks) enables to have a better understanding of the different elements that must perceived by AI functions in a train. It is worth noticing that we firstly tried to differentiate the external (i.e., outdoor) environment from the internal (i.e., indoor) environment. Then, for each environment, we classify the different perceptions by type, function, or operation. In our analysis, we focused on the activities and missions of the driver during the driving operations (i.e., from taking service until the end of service) and other driving staff tasks.

The objective is to identify the elements that should be continuously monitored in the train environment which consists in:

- Identifying implicit driver perception tasks and staff (human operator), indoor and outdoor.
- Identifying explicit driver perception tasks defined in standards and procedures.

In a non-exhaustive way, these various activities are listed in which includes various elements of perception that the driver uses to ensure safe driving of the train.

Table 9-1: List of perception tasks: driver and staff (human operator).

| Driver perception tasks | Outdoor environment | Indoor environment |
|---|---|---|
| **Visual perception (Sight)** | Signaling/signs, people, animals, moving objects, static objects, weather conditions, Infrastructure status, intention perception, tracking, distance of the objects | People, moving objects, static objects, fire, smoke, |
| **Auditory perception (Sound)** | Precise oral instructions, voices and cries, other vehicles, specific sounds of the train in operation, specific rail, other sounds | Voices and cries, specific sounds of the train in operation, train components, other sounds |
| **Olfactory perception** | detection of fire, and other peculiar smells, etc. | detection of fire and other peculiar smells, overheated components, etc. |
| **Kinaesthetic and vestibular** | Speed and acceleration, breaking, | Speed and acceleration, vibrations and shocks |
| **Others** | Localization and weather conditions | Temperature, humidity, fire, smokes, signals indicating the status of some subsystems |

## 9.3.2 Step 2: Identification of AI perception functions

From the analysis process above, we have identified more than 60 perception tasks, which have been classified into 10 AI perception functions. Table 9-2 provides a short description for each perception function that can be deployed for autonomous train GoA3/4.

Table 9-2: AI perception functions for autonomous train.

| AI perception function | Description | Grade of Automation (GoA) |
|---|---|---|
| **Obstacle detection** | The obstacle detection function aims to detect (and in some case to recognize and identify) any obstacle (static or in movement) that engage the gauge of the train and can provoke an accident (collision, derailment, etc.) | GoA3/4 |
| **External environment monitoring** | The environment monitoring function aims to collect information and extract relevant knowledge from the railway environment surrounding the train (except the track line, which is a part of the obstacle detection domain). The environment monitoring function detects, identifies, and recognizes all persons (infra workers, passengers, etc.) animals, objects, and railway elements being surrounding the train. | GoA3/4 |
| **Sign/Signal recognition** | The Sign/Signal recognition function aims to continuously detect and identify the railway signalling information necessary to the safe driving of the train. The signalling information can be provided by the lateral lineside signalling system or signs given by the railway staff. In addition to detecting the correct aspect of the signals, the function shall detect abnormal, missing, and ambiguous signal aspects. | GoA3/4 |

| AI perception function | Description | Grade of Automation (GoA) |
|---|---|---|
| **Switch and Crossing monitoring** | The switch and crossing monitoring function aims to identify the real status of the switch position (correct or wrong position) and to detect its component failures (e.g., missing bolts, damage rail pad, broken base plate, flexural cracking etc.) | GoA3/4 |
| **Infrastructure supervision** | The infrastructure supervision function aims to detect and recognize the railway infrastructure elements, their status and failures | GoA3/4 |
| **Passengers' supervision** | The Passengers' supervision function aims to detect, identify, and characterize passenger activities and behaviors inside the rolling stock. It consists also in detecting the presence or not of passenger in the train and count their number if possible. | GoA4 |
| **Platform monitoring** | The platform monitoring aims to supervise the train when entering or leaving the platform. The main objective consists in avoiding any incident or accident on the platform or leave the platform. | GoA3/4 |
| **Rolling stock monitoring** | The rolling stock monitoring aims to continuously supervise the nominal behaviors of the train components and to detect any deviation, degradation, or abnormal behaviors. In addition, it aims to detect any incident or accident in the train, i.e., fire or smoke in the locomotive, etc. | GoA3/4 |
| **Train localization** | The train localization function aims to provide the train localization "objects" (e.g., trains, coaches, maintenance rolling stock, workers) positioning information along/around the track | GoA3/4 |
| **Weather information monitoring** | The weather information monitoring aims to provide continuously accurate weather and climate information (temperatures, humidity, snow, rain, wind, etc.) | GoA3/4 |

## 9.4 Conclusion

Automation in railways, in open environment, is getting more and more attention in the last years with the objective to increase safety to cope with the limitations of human operator. To achieve higher level of automation, the technical system shall replace the human operator by executing tasks such as the perceptions ones. This work presented an overview of the methodology on how to identify the list of these perception functions. The first step consists in identifying the tasks of the human driver/operator that are described in normative documents, technical reports and research work. Then, from the outdoor and indoor tasks, the list of perception functions is derived and required to deploy an autonomous train of GoA3/4. These functions are considered as safety critical. Consequently, a paramount exercise is to study the risks of integrating these perception functions in the railway system. The quantitative safety requirements shall then be specified according to the European standards and regulations.

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## 9.7 Authors

Dr. **Insaf Sassi** (She/her) has received the engineering degree from the National School of Computer Sciences (ENSI), Tunisia, in 2014; the master's degree in control systems from Ecole Centrale Lille, France, in 2014; and the Ph.D. degree in control systems from University of Grenoble Alpes in 2017. She joined Railenium as post-doctoral fellow in 2018 and then as safety research engineer to work on RAMS analysis. Her research deals with dependability and safety analysis of railways systems. She contributed to European projects X2R2 WP4, X2R2 WP3, X2R4 WP6-7, TAURO and national ones DRAISY, Autonomous train (TASV).

E-Mail: insaf.sassi@railenium.eu

Dr. **Abderraouf Boussif** (He/him) is a researcher with the France Railway Technological Research Institute – IRT–Railenium. He received the B.-Eng. degree in system control engineering from the Polytechnic High School, Algeria, in 2012, the master's degree in complex systems engineering from the École Normale Supérieure de Cachan, Paris, in 2013, and the Ph.D. degree in safety system engineering from the University of Lille, France, in 2016. He participates and contributes to safety studies and activities in national projects (DEPARTS, Autonomous Train, Railway Remote Driving, Safety assurance of AI) and European projects (Shit2Rail TAURO, EURJU R2DATO). His research interests are mainly in railway safety, safety assurance of autonomy and artificial intelligence systems.

E-Mail: Abderraouf.boussif@railenium.eu

# 10 Video and sensor streaming for remote train operation

*Katharina Hartmann, Oliver Röwer;*
*DLR, Institute of Transportation Systems, Braunschweig, Germany*

## 10.1 Introduction

Work package 2 of the EU-funded TAURO project (Technologies for the Autonomous Rail Operation) aims to provide a solution for remote driving and remote command. For remote train operation (RTO) video and sensor streaming plays a vital role. Based on considerations in the projects Lucy Train Lab and 5G Living Lab and an additional literature review this paper gives an overview of existing approaches and architectural solutions for video and sensor streaming in a safety-critical environment. Furthermore, we propose an architecture that can be utilized for video and sensor streaming for remote train operations and point out how these activities could be integrated into the operational and technical workflow.

## 10.2 Technological background

This section presents relevant technologies for streaming videos from one computer to another. First, the terms aspect ratio, video resolution, and bitrate are introduced. After that, different techniques for video encoding are presented followed by protocols for video transmission.

### 10.2.1 Video streaming

When dealing with the topic of video streaming there are some aspects to be considered. The first item is the **aspect ratio** which describes the ratio between the width and height of a video and/or screen. Nowadays, common aspect ratios are 16:9, 21:9, or 4:3. The **video resolution** explains how many pixels each frame in the video has. Typical resolutions are high definition (HD) with 1280x720 pixels and full HD with 1920x1080 pixels. The third factor, **video bitrate**, describes the amount of data that is processed per unit of time. The video bitrate is usually measured in bits per second, common bitrates for HD videos vary between 20 and 30 Megabits per second (Mbps). The higher the bit rate, the higher the level of detail. Thus, it is common for a high resolution to also use a correspondingly high bit rate.

### 10.2.2 Video Encoding

When mapping the situation, the camera first generates a stream of raw data. Depending on the resolution, this can already exceed the entire available upload bandwidth of the 5G connection. Therefore, it is state of the art for video streaming and many other video-based services to use encoding and decoding algorithms, so-called video codecs, to compress the data to be transmitted. However, not all video codecs are suitable for all purposes. While the video codec H.264 is used for many purposes like video conferences and HD television, its successor H.265 became established for ultra-high definition supporting resolutions up to 8192x4320 pixels. The codec MPEG4 was, similar to H.264, developed for audio and video encoding in multiple multimedia applications. Another open-source codec is VP8. In [1] the video codecs

H.264, MPEG4, and VP8 are compared regarding the quality of the video stream and end-to-end latency. The results show that MPEG4 outperforms VP8 and H.264 in terms of quality while H.264 has the best end-to-end delay.

### 10.2.3 Video transmission

Regarding the transmission of the video and sensor data from the onboard to the trackside the following aspects have to be considered:

- protocols in the application layer (RTP, RTCP, RTSP, WebRTC, HTTP(S))
- protocols in the transport layer (UDP, TCP)
- access / multiplex technologies (NOMA, TDMA, FDMA, OFDM)

In communication and entertainment systems that use streaming media, the Real-time Transport Protocol (RTP) is commonly used to provide audio and video over IP networks. The real-time Control Protocol (RTCP) is used in combination with RTP to track transmission statistics and quality of service (QoS) [2]. Media sessions between endpoints are created and managed using RTSP [3]. Play, record, and pause are just a few of the commands that make real-time control easier.

All three protocols, RTP, RTCP, and RTSP, must be used for a video streaming application to work properly.

WebRTC is an Application Programming Interface (API) that enables real-time audio and video communication between web browsers and mobile applications [4, 5]. The video codecs H.264, VP8, and VP9 are supported by WebRTC across all browsers and once more utilize RTP. When the endpoints do not have public IPs, that is, they are hidden behind a NAT or firewall device, WebRTC enables media session establishment by utilizing Session Traversal Utilities for NAT (STUN) and Traversal Using Relays around NAT (TURN) servers to commence the connection.

A secure communication protocol for computer networks is HTTPS. Dynamic Adaptive Streaming over HTTP (DASH), commonly known as MPEG-DASH, is a high-quality adaptive bitrate streaming solution for media supplied via traditional HTTP web servers over the Internet. On the one hand, the statelessness of DASH offers the benefit of preventing streaming failures during handover procedures. Contrarily, every video chunk is supplied in response to an HTTP GET request, which adds at least 1 second of latency even when a chunk's length is reduced. [6]

The most used transport layer protocols are User Datagram Protocol (UDP) and Transmission Control Protocol (TCP). Since TCP is connection-oriented, a connection must first be made between the client and server in order to send data. Additionally, TCP offers applications on an IP network reliable, orderly, and error-checked delivery of a stream of data. TCP is considerably sluggish because of the guaranteed delivery of data, which is done by retransmitting data when a packet is defective or lost. As a connectionless protocol, UDP cannot ensure that sent data will arrive in the correct sequence or be protected from duplicate transmissions. UDP is substantially faster than TCP since there aren't any handshaking conversations or retransmissions like there are with TCP. UDP is, thus, often employed in time-sensitive applications.

Within the access technologies, we consider Frequency-division Multiple Access (FDMA), Time Division Multiple Access (TDMA), Orthogonal Frequency Division Multiplex (OFDM), and Non-Orthogonal Multiple Access (NOMA).

In the Time Division Multiple Access (TDMA) and the Frequency Division Multiple Access (FDMA) multiple users will be allocated different time and frequency resources in an orthogonal manner. NOMA allows users to share the same time and frequency resources which leads to higher spectral efficiency [7]. Furthermore, according to [8] NOMA achieves better performance compared to other orthogonal multiple access techniques.

## 10.3 Related Work

In recent years there has been a lot of work on the topic of remote driving and, thus, video and sensor streaming from vehicles to remote operator's places. As there is only little research on video streaming for RTO, work in the context of remotely driven cars is also considered.

Bećirbašić et al. proposed 2017 a video-processing platform for semi-autonomous cars over 5G [9]. To prevent blind spots the test vehicle was equipped with 10 cameras with overlapping fields of view with a resolution of 1280*720. For remotely driving a car the authors stated there has to be a maximal latency of 50 ms, which means that 4G networks are ineligible. In addition to the cameras, multiple sensors were integrated into the vehicle. In [10] they enhanced the considerations to a virtual cockpit application with three screens and proposed a solution for a maximum target speed of 50 km/h. To comply with a maximal latency of 70 ms (so the car would not have moved more than 1 m) the H.264 video codec, a bitrate of 10-15 Mbps, and a lower video resolution of 720*480 for two of the three video streams were used.

In 2018 Kang et al. tested various communication protocols, bitrates, and resolutions in the context of remotely driven cars [11]. A single raw video was compressed with H.264 or MPEG-4 video codec which resulted in a reduction of 5-15 % per frame. The researchers transmitted the video via UPD using LTE- or WiFi-based communication. In addition, multiple bitrates (0.5, 1, 4 Mbps) and different resolutions (320x240, 640x480, 1280x960) were considered. To record the relevant parameters, they used an app for measuring e.g. the latency. There was a median latency of 100 ms for LTE-based connections and 50 ms for transmissions via WiFi. The frame loss rate varied from 0.5% to 2% for different bitrates and resolutions. Even though the paper described various combinations the researchers did not recommend a resolution, bitrate, or video quality based on their results.

Yu and Lee proposed in their paper 2022 a UDP-based video transmission for remote driving systems [12]. While the transmission of commands requires control mechanisms to prevent data loss or faulty information, the main aim of the video transmission is low latency. As UDP has a limit regarding packet size the frames have to be split. The proposed solution was tested with model cars at a speed of ca. 65 km/h.

RTO is in combination with Automatic Train Operation (ATO) a growing market in the railway sector since 2019.

In September 2019, Lucy Train Lab performed remote driving via 5G for the first time [13]. Lucy Train Lab is a modified train with integrated cameras to monitor what's happening on and around the train. One use case is a remotely operated trip from a storage area to a platform. For this, the camera images must be transmitted to the remote operator without any noticeable delay and in good quality. The remote operator's workstation has a display that shows the information of the Human Machine Interface (HMI) of the train and also an operating lever to properly steer the train. The train is equipped with an intermittent automatic train running control (PZB, short for German "Punktförmige Zugbeeinflussung"), Continuous Train Control (LZB, short for German "Linienzugbeeinflussung"), an ETCS-capable on-board unit (OBU), LiDAR sensors, thermal cameras as well as GNSS and cellular antennas. Furthermore, the driver's cab has an inertial measurement unit (IMU), and stereo and infrared cameras with a high-speed ethernet interface. A high-definition industrial camera (Nano-C1930 Teledyne DALSA) with 80 frames per second (fps) was chosen. This camera has advantages over common surveillance cameras as there is no internal compression and, thus, no additional latency. The individual frames were compressed via Motion JPEG. The video was streamed from the onboard system via VPN to the remote operator's workstation at 25 fps and approximately 85 kbytes/frame in 1200 x 1000 pixel format. In addition to transmitting camera images, an application on the remote operator's workstation displays the train's platform-specific geographic location. Work on Lucy will continue in follow-up projects as part of the 5G Living Lab.

In 2020 the results of the TC-Rail project, a partnership formed by SNCF, Thales, Actia Telecom, CNES, and Railenium, on safe remote driving without a driver in the train cabin were presented [7]. The project was the first proof of concept for remotely driving a train without European Railway Management System (ERTMS) infrastructure at a maximum target speed of 100 km/h. The paper compares LTE and 5G systems and concludes that 5G is in all situations superior to LTE. Additionally, the case of two trains in the same cell was considered. The authors proposed using NOMA for the allocation of resources in the channel to guarantee good performances for both trains.

## 10.4 Proposed architecture for video streaming

Based on the literature review and experience from projects like Lucy Train Lab we propose a general architectural solution for video streaming in the context of RTO. The proposed architecture for streaming video data is shown in Figure 10-1 and is based on the high-level functional architecture for remote driving that was developed within the project TAURO.

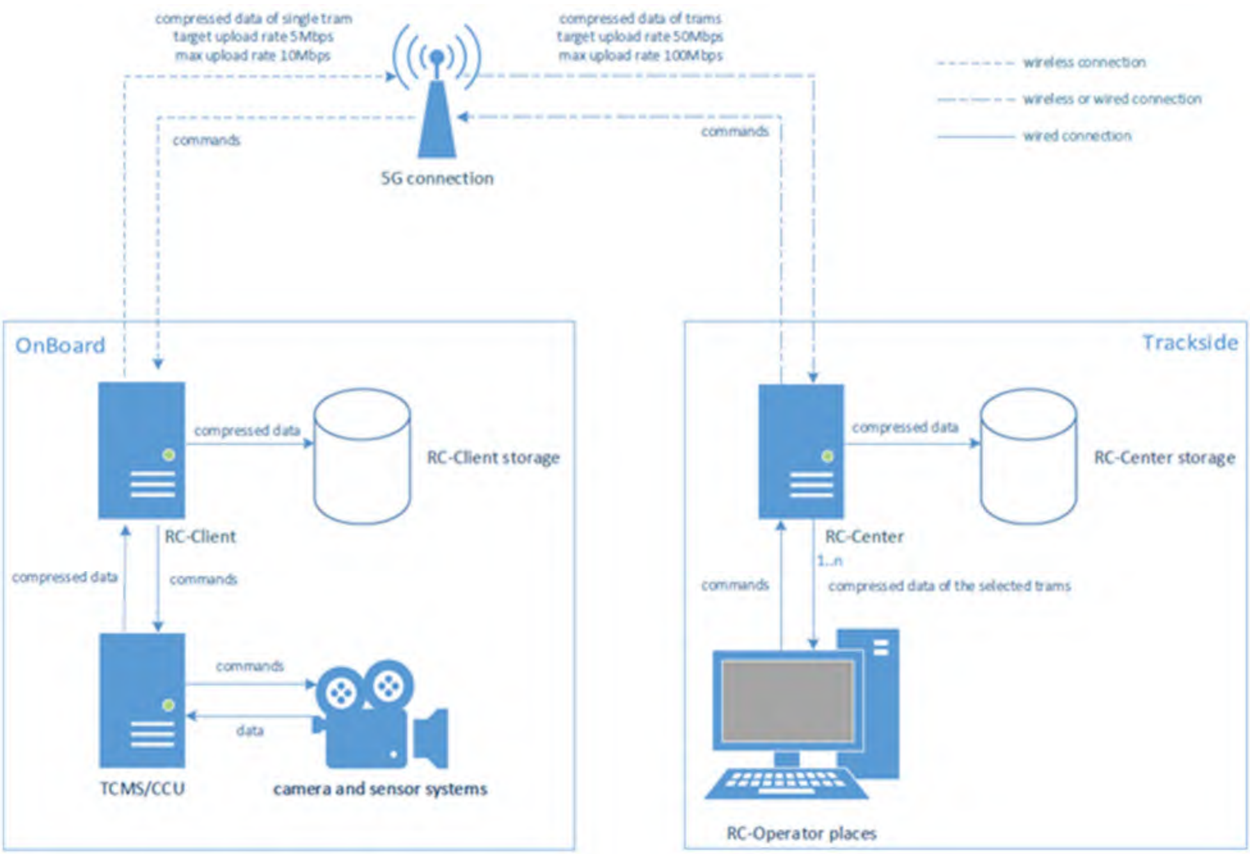


Figure 10-1: Proposed architecture for video and sensor streaming

The presented system consists of an onboard and trackside system with a Remote Control (RC) client and a RC center respectively. Additionally, the onboard system includes Train Control and Monitoring System (TCMS) to which the cameras and sensors are connected and a storage for recorded video and sensor data. We propose the use of industrial cameras without internal compression to avoid additional delay due to internal compression. Based on similar research and projects in [12], [11], and [9] we propose a video resolution from 640*480 px up to 1280*720 px. As the video has to be compressed before the transmission the video codec H.264 should be used to ensure low latency and suitable quality at once. The storage is crucial since it allows for reading out of what occurred during the absence of a corresponding transmission, even if a connection is lost. This could be particularly vital for the study of accidents.

The RC client transmits data to the RC center using a 5G connection to a linked radio tower at a targeted upload rate of minimum 5 Mbps which is considered a requirement for RTO within TAURO. For the transmission of video and sensor data the network protocol UDP and the RTP respective RSTP are frequently used. Thus, we propose to use UDP in the transport layer and RTP in the application layer. As no browser application is involved, WebRTC does not have to be used. A VPN connection is reasonable to decrease glass-to-glass latency and safeguard the data from outside cyber assaults. It is possible that the 5G tower is reached by a number of rail vehicles. Therefore, NOMA should be considered as an access technology to allow for multiple trains in the same cell. The tower transmits all incoming data from the various RC clients to the corresponding RC center. Here, the data is also stored in order to support, among other things, an accident analysis even if the data already stored on the rail vehicle is no longer accessible.

The video and sensor data are now decompressed and transmitted to the designated RC operator place. The aspect ratio depends on the preferred screen size at the remote workplace. The RC operator now has the possibility to process the data according to his activity and to transmit necessary control signals and instructions to the train.

### 10.4.4 Extension of the architecture for additional sensor information

In addition to the visual perception of the train's surroundings by the remote driver by means of using a camera, further sensors can be installed in the train. The remote driver needs knowledge of the train metadata in order to operate remotely. This incorporates data on the position obtained using GPS or GNSS receivers as well as speed, as determined, for instance, by an odometer or radar sensor. Additionally, while operating the train, train drivers would experience both audio and visual sensory experiences. From a psychological perspective, adding noises through the proper microphones can be a helpful complement to the video stream because it can improve the remote operator's situational awareness, especially in case of low video quality [14]. Additionally, the video data can be processed so that automatic object detection in the image aids in remote control operation or even starts automatic procedures, like emergency braking, to prevent a collision with an object on the track. Radar or lidar systems are examples of sensors that assist in the identification of potential threats on the track.

The data volumes of sensor systems in addition to the camera sensor technology also have an effect on the network load and, in particular, on the upload rate required per train. It can be assumed that the resulting data volumes are comparable to or even exceed those of the video stream. A remedy for this can be a digital map in which objects detected by the other sensor systems are noted and ultimately only these objects are transmitted.

### 10.4.5 Integration of video and sensor streaming in the operational and technical workflow

To pave the way for RTO the video and sensor streams have to be integrated into the remote operator’s workflow.

The first aspect to be considered is the coherence between the sensor data and the video stream. To ensure that valid information is presented to the remote driver, the video data that the remote driver sees should have been generated at the same time as the simultaneously arriving sensor data. However, other shared variables like system status have to be synchronized as well. Therefore, the architecture has to ensure that outdated video and sensor data are discarded. This could be implemented with a time stamp that is created onboard and verified on the remote side. If the incoming data have a time stamp that is more than one second behind the data should be discarded.

Furthermore, there are a variety of possible causes that can lead to the impairment of the remote control. In the following the interference that directly affects video and sensor data transmission is explained.

Once a connection has been established and the remote driver is active, it is conceivable that the train will enter an area that is not sufficiently well covered by 5G. In this case, the available bandwidth and thus the potential upload volume drop. Thus, the high-resolution camera images may no longer be transmitted in the required quality. These deteriorated connection conditions can also lead to an interruption in communication. A comparison with the predecessor of 5G shows that, although the construction and expansion of the 4G network began in 2010, even today there are repeated connection drops during train journeys. Since remote driving on open tracks is also considered in TAURO, this problem may also occur with 5G. The project also considers shunting in shunting yards, and as coverage of such a delineated area is much easier to implement, the occurrence of this type of interference can be more easily prevented here.

A similar interference occurs when there is enough bandwidth available, but it has to be divided among too many participants. Particularly when multiple trains are in the shunting yard, the 5G network can become overloaded. In this case, it is necessary to consider whether one or more masts should be erected specifically for the shunting yard in order to counteract overload.

In addition to inadequate bandwidth, disruption can also occur due to hardware defects on the train itself. For example, the cameras, power or data lines, and computer hardware that processes the recorded video and sensor data could fail. As the video and sensor data are stored on the train, there

Interference with video and sensor data transmission can also result from the train having an insufficient amount of power to turn on or run the required hardware.

However, the disruptions that are specifically relevant for video and sensor streaming are poor connection quality, network congestion, or the disruption of corresponding hardware and software elements such as sensors, cameras, and systems that are then supposed to make this data available to the remote operator via the network.

If disruptions cause such a poor connection that remote control is not possible or even a connection abortion there have to be procedures so the drive is not interrupted. The question of which procedures should be applied in such a case and what aspects determine the triggering condition requires further research.

## 10.5 Conclusions

In summary, this paper gives an overview of necessary considerations regarding remote train operation. First, the theoretical background information was presented. Then, we discussed related work in the context of remote driving of cars as well as trains. Especially the experiences from the project Lucy train laboratory and the project 5G Living Lab have influenced this paper. Based on the literature review we proposed an architectural solution for video and sensor streaming for RTO. Especially in 5G networks, new access technologies, e.g. NOMA, should be considered to allow for multiple trains in one network cell. Furthermore, we considered possible disturbances in the technical and operational workflow and how the proposed architecture can prevent long-term interruptions.

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## 10.9 Authors

**Katharina Hartmann** has been a research associate at the DLR Institute of Transportation Systems since 2020. Her work focuses on testing components for rail and automotive communications as well as project management. Katharina holds a degree in computer science and is currently deepening her knowledge in technology-oriented management with a focus on service design for digital products.

E-Mail: Katharina.Hartmann@dlr.de

**Oliver Röwer** has been working at the RailSiTe® test laboratory of the DLR Institute of Transportation Systems since 2013 as a computer scientist. His research area is test methods and approval methodologies in the railway domain for command, control and signaling technologies. This includes in particular the construction and further development of test laboratories and simulation systems in the area of Automatic and Remote Train Operation.

E-Mail: Oliver.Roewer@dlr.de

# 11 Introduction to Moving Block Specification

*Stefanie Schöne; DLR, Institute of Transportation Systems, Braunschweig, Germany*

## 11.1 Introduction

This contribution introduces the Moving Block Specification developed in the X2Rail projects and finalized in X2Rail-5. It shows examples of new concepts that are introduced in order to deal with the new constraints Moving Bock Systems will face.

## 11.2 Structure and contents of the X2Rail-5 Moving Block System specification

One goal of Shift2Rail is to provide demonstrators that implement European Train Control System (ETCS) Level 3 Moving Block systems. These systems shall conform to the existing ETCS specifications. However, as the specifications apply to all levels of ETCS, some of these requirements have to be stated more precisely for Level 3 to reach the level of detail needed to develop individual, interoperable ETCS systems. To aim for the different needs of the market, the system specification fits all different railway operation systems (High speed, urban, freight and overlay systems) as well as the four railway types:

- Full Moving Block with Trackside Train Detection (TTD),
- Full Moving Block without TTD,
- Fixed Virtual Block with TTD and
- Fixed Virtual Blocks without TTD

The Moving Block Specification is carried out in the dedicated Work Package 4 “Moving Block” of X2Rail-5. The Deliverable 4.1 [1] contains the system specification in six different parts:

- Part 1 Introduction – including used terms, abbreviations and references for all six parts,
- Part 2 System Definition – defining the system and stating assumptions,
- Part 3 System Specification – containing requirements for the Moving Block System,
- Part 4 Operational Rules – for operator interactions needed in the system,
- Part 5 Engineering Rules – for cases in which additional rules or configurations are required, and
- Part 6 Safety Analysis – containing a generic Hazard Analysis, while a full Safety Analysis has to always be executed for a specific system implementation

## 11.3 Basic principles of the Moving Block system

### 11.3.1 Approach and Constraints

The Moving Block System specification is implementation and technology independent. This means it shall cover all critical safety concerns, basic principles of system design and implementation of interfaces, all the while leaving operators and system manufacturers enough room for their specific implementations and to follow national peculiarities. For example, the development of a safe Moving Block System is possible that works completely without physical trackside signals or TTD. However, there are engineering rules that give a guidance to where additional TTD could improve possible safety or line capacity issues.

The specification aims to be compatible with the existing ETCS specification, specifically Baseline 3 Release 2 [2], already assuming Change Request 940 [3] as included. The Moving Block Specification only describes the rules and requirements that go beyond these already existing for a Level 2 system and therefore does not contain the specification for a whole ETCS system. For the functionalities of Level 2 systems the already existing ETCS specification has to be consulted. This is also the reason why most of the stated requirements in the Moving Block Specification are for the Trackside part of the system as this contains the most differences between Level 2 and Level 3 systems.

What parts of the railway system the specification covers is shown as the indicated "ETCS L3 System" in Figure 11-1.

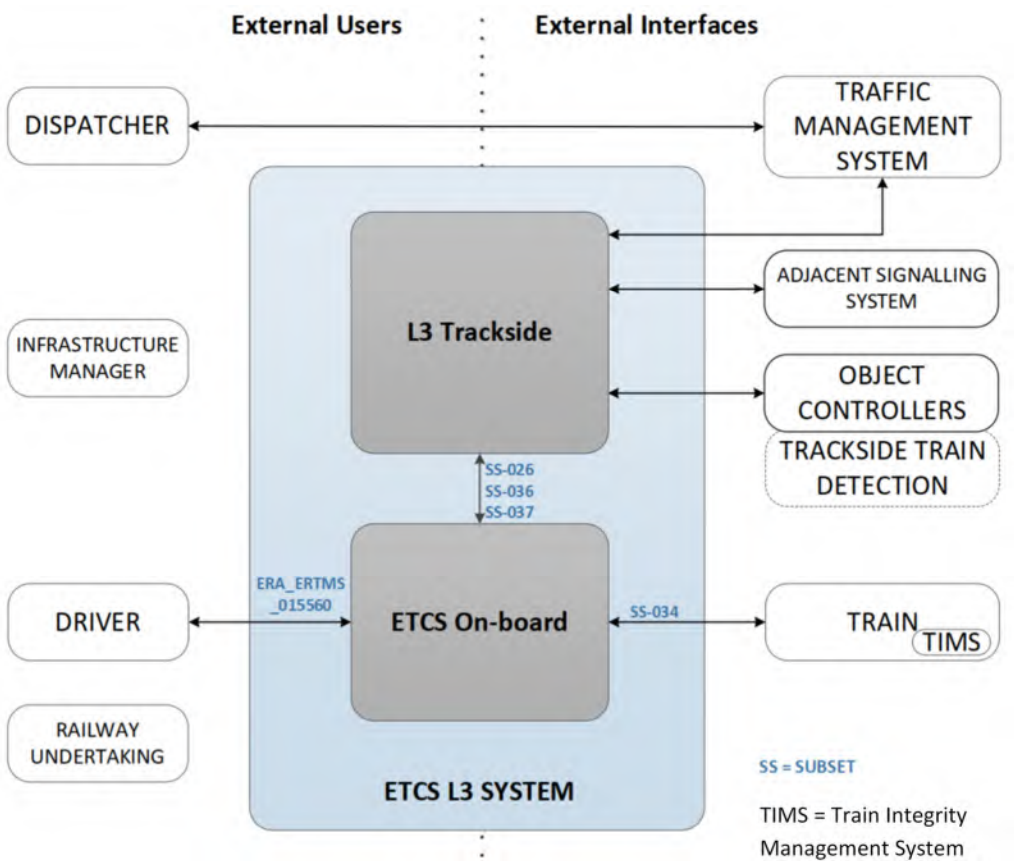


Figure 11-1: Moving Block System Boundaries, from [1]

The following sections show two examples of new concepts that were introduced to deal with the constraints for Moving Block systems.

### 11.3.2 Track State Management

A crucial part of ETCS Level 3 is the fact that the Trackside has to have a clear picture of the track occupation status in their area in order to issue safe Movement Authorities, based only on Train Position Reports. To represent the Track, each section of the track can have the Track Status "Occupied", "Clear", or "Unknown". "Occupied" and "Clear" representing a clear information about the presence of a known obstacle on the track. "Unknown" is issued if it is not clear if there is an obstruction or if the system is sure that there is a train in a certain area, but not sure where exactly. There could be various reasons for a Track Status Area to be "Unknown", including:

- Trains without confirmed Train Integrity
- Trains not communicating
- Areas created by the dispatcher, in order to secure areas, for example construction sites

The full list is part of [1]. "Unknown" Areas can be cleared by various means, for example by sweeping with train movements. On the other hand, there are also non sweepable "Unknown" Areas, to remain "Unknown" after a train has passed.

Additional to the Track Status, the Track State Management introduces the concept of a Reserved Status. Reserved meaning to be dedicated for the movement of one assigned train in a specific direction. This enables the Trackside to issue Movement Authorities of any length at any convenient timing, as long as they are issued within the Reserved Area for that train. This concept also provides the safety layer, as a train can generally not enter in a Reserved Area for a different train.

The Track Status is determined from a variety of information sources available to the Trackside, usually including TTD, TIMS and other sources that may be available to the TMS, as the dispatcher. How the logic of Track State Management can be applied to the different railway system types, is shown in Part 3 of [1].

### 11.3.3 L3 Margin

Part of the works in the Moving Block Workstream of the X2Rail projects was to analyze possible risks introduced by the new conditions when operating in Moving Block, and to introduce requirements in the specification to mitigate these risks. One of the issues was the risk that a train overpasses its issued Movement Authorities. This risk is higher than in Level 2, because the Movement Authority can be set up to the very rear of the preceding train, as indicated in Figure 11-2. Additionally, in certain implementations without TTD, it could be that a train is unintentionally rolling back into the Reserved Area of the following train.


Figure 11-2: One train following another in Moving Block, from [1]. Green indicating the Reserved Area for Train 2, Red indicating the Occupied Track Status Areas

In the safety analysis, it is concluded that it is unlikely that both situations described above will occur and pose a risk at the same time. The Moving Block Specification requires the use of a so called "L3 Margin", that is set between the rear of a train and the end of any Movement Authority for a train following it. However, how large this Margin may be, and if it might have different values set for different circumstances, is up to the specific implementations, national rules and specific risk evaluations in every case.

## 11.4 References

[1] X2Rail-5 Deliverable 5.1: Moving Block Specification, available under: https://projects.shift2rail.org/s2r_ip2_n.aspx?p=X2RAIL-5

[2] Set of specifications # 3 (ETCS Baseline 3 Release 2 and GSM-R Baseline 1) according to Annex A of Commission Implementing Regulation (EU) 2019/776 of 16 May 2019. It is publicly available:
https://www.era.europa.eu/era-folder/set-specifications-3-etcs-b3-r2-gsm-r-b1

[3] The Change Request 940 is held within the ERA Change Request database, together with the proposed solution.
The solution is publicly available within Opinion ERA/OPI/2020-2:
https://www.era.europa.eu/library/documents-regulations/opinions-and-technical-advices
The description of CR940 is available in Annex 3 of the above. The solution has subsequently been updated in the ETCS CCM process, but without impact on the Moving Block Specification.

## 11.5 Acknowledgements

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Disclaimer: This dissemination of results reflects only the authors' view and the Shift2Rail Joint Undertaking is not responsible for any use that may be made of the information it contains.

Europe's Rail

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## 11.6 Author

Dipl.-Ing. **Stefanie Schöne** finished her studies of transport engineering at the Technical University of Dresden, Germany with a diploma in 2012. Since then she has been working at the Institute of Transportation Systems of the German Aerospace Center (Deutsches Zentrum für Luft- und Raumfahrt, DLR), mainly in the fields of railway operations and railway signalling systems.

E-Mail: Stefanie.Schoene@dlr.de

# 12 A New Formal Methods Guidebook for the Railway Signalling Domain

*Daniel Schwencke; DLR, Institute of Transportation Systems, Braunschweig, Germany*
*Arne Borälv; Prover Technologies, Stockholm, Sweden*
*Luis-Fernando Mejia; Alstom, Paris, France*

## 12.1 Motivation for the Guidebook

Considerable know-how about formals methods (FMs) exists in the railway signalling domain [1, 2], and FMs have been successfully applied e.g. for verification of interlockings [3] or development of computer-based train control systems [4]. Some railway infrastructure managers, such as RATP, New York City Transit, Stockholm Metro and Trafikverket even prescribe formal safety verification for some types of relay-based or computerised interlocking systems. But FMs expertise is not generally available or widespread, and apart from a general recommendation in [5], there is a lack of FMs integration into standards, of recommendations for FMs use and of guidance on where and how to employ them. For these reasons, and due to interest from Europe's Rails System Pillar, TD2.7 of Shift2Rail is currently preparing a FMs guidebook as part of the work in WP10 of the X2Rail-5 project. This guidebook expands on X2Rail-2 work [6] and aims to document know-how, experience, and recommendations, to pave the way for wider use of FMs.

The scope of the guidebook includes today's and future railway signalling systems; its view on FMs is geared towards typical properties and conditions of these such as high RAMS[1] requirements and high configurability. The target audience includes infrastructure managers, suppliers, railway engineers, railway signalling initiatives and projects.

In the following, the guidebook contents are briefly presented, including why, when and for what purpose to apply FMs, what FMs are and which steps their application follows. Afterwards, an example application of the guidebook's FMs concepts is described, based on WP10's FMs demonstrator for ETCS[2] Level 3 with moving block. Finally, a summary, conclusions from the guidebook creation, and an outlook on the finalisation of the guidebook are given.

### 12.1.1 Reasons to Apply FMs (Now)

Current developments like upcoming new functionality (ATO[2], moving block, train integrity, new train positioning approaches) and new modular standard architectures (EULYNX [7], RCA[2]

[1]Abbreviations: RAMS = Reliability, Availability, Maintainability and Safety; ETCS = European Train Control System; ATO = Automated Train Operation; RCA = Reference CCS (Control Command and Signalling) Architecture; SIL = Safety Integrity Level; V&V = Verification and Validation.

[8], and their continuation in Europe's Rails System Pillar) constitute both a request for the capabilities provided by FMs and a unique opportunity to introduce FMs on larger scale. In this situation of growing system and especially software complexity, FMs can be a valuable, meanwhile mature tool to maintain safety and to limit time and costs spent on a signalling system during its life cycle. The main gains from FMs use are presented in Table 12-1.

Table 12-1: Benefits from FMs w.r.t. current challenges in railway signaling

| **Aspect** | **Current situation** | **How to benefit from FMs** |
|---|---|---|
| Time-to-market and predictable schedules | Long and unpredictable schedules, systems costly to procure, develop and maintain | Improve quality of system requirements and tenders using FMs, to find issues earlier, reduce complexity, enable reuse and standardise |
| High RAMS demands | Traditional methods for specification, architecture, design, implementation and verification of SIL[2] 4 software prevalent although laborious and higher risk of residual errors | Raise trust in and quality and verifiability of implementations, due to *formal verification*[2] of critical system properties (e.g. safety, interoperability), automation of tedious V&V[2] tasks, and valuable feedback, insight and helps to detect and correct mistakes |
| New system principles | ETCS "game-changer" technologies (ATO, moving block, …) are being specified, aiming to become part of future harmonised standards versions | Define principles and perform analysis and V&V of requirements before harmonisation/ standardisation, to ensure clear and verifiable specifications that multiple stakeholders understand and which ensure safety |
| Modular architectures and standardisation | Infrastructure managers expect future systems to implement new, modular architectures, to increase competition, reduce costs and support the long-term evolution | Perform *formal development* of a reference model that implements principles and requirements apportioned to its components, to validate the new requirements and processes, foster high-quality modular safety cases, and enable different analyses (e.g. impact analysis, safety, degraded modes, configurability) |
| Knowledge capitalisation | Expert staff is a scarce resource and bottleneck, many tasks are carried out manually based on expert judgement, for which long experience in railways is required | Use FMs to promote knowledge capitalisation, enable reusability, precise impact analysis and more independence from domain expertise. Use expertise to define and maintain principles and requirements that can be reused, and to prepare automated V&V processes, if possible |

[2] An explanation of terms in italics is provided in Section „12.3.5 FMs Taxonomy" below.

# 12.2 Where to Apply FMs

## 12.2.2 FMs in the System Life Cycle

The guidebook distinguishes four high-level (HL) phases of a system life cycle in which FMs may be used. They correspond to different roles of FMs in a life cycle and serve as structural basis for presenting FMs uses and recommendations. The phases are presented in Table 12-2 including their names, correspondences to phases from the CENELEC standard [9], relevant activities, possible FMs uses and considerations for being FMs friendly in each phase.

Table 12-2: Activities, FMs use and how to be FMs friendly in the four high-level phases defined in the guidebook (reqs = requirements, SRACs = Safety-Related Application Conditions)

| **Activities** | **FMs use** | **Being FMs friendly** |
|---|---|---|
| HL1 – Define Standard Principles and Requirements (CENELEC phases 1-4) | | |
| • Gain understanding of user reqs (e.g. by prototyping)<br>• Formulate and refine implementation-independent ontology<br>• Define contracts between concepts or known subsystems<br>• Create and refine a reference design<br>• Specify mandatory principles and reqs | If activities use FMs, properties will be made precise through formalisation and may be formally proved consistent and preserved during system operation. This will result in well-founded standard principles and high-quality reqs, enabling reuse and a competitive market. FMs use in this phase means most likely extra effort, but will pay off in later phases. | • Identify desired (interoperability, safety, reliability, standards compliance) system properties early (in this phase)<br>• Establish provability of properties early (in this phase)<br>• Strive for self-contained reqs |
| HL2 – Architecture and Design (CENELEC phase 5) | | |
| • Decompose system<br>• Apportion reqs to subsystems<br>• State assumptions on respective subsystem environment explicitly<br>• Define interfaces between subsystems | • Analysis/V&V of system-level reqs, degraded modes and system initialisation when decomposing the system<br>• Validation of operational procedures whether they fulfil assumptions on system environment<br>• Verification of communication protocols | • Apportion reqs and assumptions such that important system-level properties can be formally verified<br>• Provide abstractions of interfaces suited for FMs use |
| HL3 – Implement a System (CENELEC phases 6-8) | | |
| • Implement system (as configurable generic application) based on reqs, architecture and design | • Define and verify consistency and correctness reqs for configuration data<br>• Verify generic application or instantiated generic application against reqs<br>• Prove generic properties of code (termination, no dead code, …) | • Formally verify safety properties & consistency during development (not just afterwards)<br>• Carefully select a set of system configuration that exercise a suitable level of coverage of the reqs |

| Activities | FMs use | Being FMs friendly |
|---|---|---|
| HL4 – Assess a System (CENELEC phases 9-10) | | |
| • Collect all SRACs established in previous phases<br>• Validate compliance of the system with the reqs<br>• Collect SRACs from failed verifications | • Verify reqs in scope (at least safety reqs) and demonstrate SRAC sufficiency<br>• Apply additional techniques (e.g. proof checking) in case traditional assessment is to be replaced completely<br>• Perform safety assessment independent of previous phases | • Provide appropriate system/code interfaces for verification of reqs<br>• Avoid complex/non-FM-supported code constructs |

### 12.2.3 Example Purposes for Using FMs

**System Inception**. A new (type of) system needs to be defined. To identify and define the "right" core concepts, their relations and necessary assumptions (e.g. on the system environment) that will represent a common view of the system, a high-level formal model of the system is created and analysed whether it meets expectations, allows for important usage scenarios, and fulfils basic properties. Model and properties may be refined/reused in later phases e.g. as reference by different actors in projects.

**Tender Creation & Verification of Implementation(s) against Tender**. Tender requirements are provided to suppliers to implement systems that comply with them. Using a process based on FMs can provide clearly defined tender requirements with less room for interpretation, and formal verification can be used to verify compliance of the implementation to (relevant parts of) the tender. FMs use by suppliers is not necessarily required for this use case.

**Development of System Implementation(s)**. A supplier develops system implementations with the help of FMs, using a process for formal development. The latter means that formal specification and formal verification of system requirements / desired implementation properties are applied to dynamic behaviour and/or static data during the conversion of the system specification into an implementation.

Safety Verification of System Implementation(s). A system has been already developed. The purpose of FMs use is to perform formal verification of safety requirements against a (revenue service) implementation model, to identify any deviations. If formal verification of safety requirements has been carried out already during development, this may help (in various ways) to complete this purpose.

**Testing Support**. Formal system models can be used for test case generation and, if they are executable, for system simulation. Some test case generation tools rely on formal techniques.

## 12.3 Understanding What FMs Are

### 12.3.4 General Overview

A FM enables formalising and analysing the static and dynamic characteristic properties of systems using mathematical models. Typically, a FM has three components:

- A graphical or textual notation whose syntax is defined by a grammar and whose semantics is mathematically defined, allowing for formal proofs.
- A methodology for using the notation to create meaningful and relevant models.
- A set of tools for creating and analysing models, including formal proofs.

There are many different FMs. They may differ in their system model paradigm – e.g. state-based, transition-based, (a)synchronous communications-based – and in their underlying mathematical formalism – e.g. (temporal) set theory, (temporal) automata, type theories.

FMs allow the rigorous formalisation of requirements on the system, and on its design or implementation, and the comprehensive verification of their correctness and consistency. In doing so, FMs allow the improvement of both, the quality of the system's requirements and the conformity of the system's implementation to them.

FMs can be used for the specification, design and verification of software and hardware systems. Experience shows [10] that FMs do not solve all problems of system development: When used for specification, where they are most beneficial, they can raise issues, but they do not guarantee the completeness and relevance of the specification (will not fill the gaps).

Also, FMs do not eliminate the intrinsic complexity of systems. Even with FMs, which certainly help to manage or even to reduce complexity, complex systems can remain difficult to model and analyse. Finally, applying FMs is not self-evident. Important factors of successful FMs use can include:

- A process and organisation of development taking FMs into account.
- The availability of staff experienced in applying FMs to systems of similar complexity in a similar context.
- The close collaboration of FMs staff with system engineers.
- The nature of people who willingly and enthusiastically apply FMs.

### 12.3.5 FMs Taxonomy

The guidebook distinguishes different FMs activities:

**Formal specification** is used to formalise and analyse the definition of a system: It creates a model of the static and/or dynamic characteristic properties of a system, which allows to better understand the system and/or to verify that the model is consistent.

**Formal verification** is used to check that a specification, design or implementation of a system complies with requirements on the system. Based on the purpose of the model, this can check that the model is consistent, that certain properties always hold, or that the model is consistent with another (reference) model.

**Formal development** is used to implement a system based on formal specification and formal verification integrated into the development process. Formal development therefore includes creating a formal implementation model according to definition and implementation constraints.

### 12.3.6 Typical Techniques Applied as Part of FMs

**Divide and conquer** is the process of dividing a problem into smaller, simpler subproblems, whose solutions can be composed to solve the original problem. Functional decomposition is one of many examples of this technique.

**Property-oriented reasoning** is the process of formalising a system by the properties it must satisfy rather than by the ways it satisfies them. State invariants and assume/guarantee properties, guards and pre- and postconditions of actions are examples of properties.

**Abstraction** is the process of representing a concept of the system in a simplified form, only including what is needed for the modelling purpose. Generalisation is a form of abstraction: it represents different concepts of a system with common properties by a single concept.

In addition, there are **specific tool-supported techniques**, including

- model transformation – e.g. generation of a formal model from a specification model, design model, or from a software implementation,
- model animation/simulation/execution, which may be used to analyse and validate system behaviour,
- proof search and counter example generation (used for formal verification),
- proof checking, for verifying that a given proof indeed is a correct proof,
- debug capabilities, to isolate and understand the cause of a dynamic situation involving system requirements, and
- test case generation, to automate creation of test suites.

### 12.3.7 Applying FMs

The FMs guidebook describes a generic process for FMs application that aims to be independent of purpose, life cycle phase, notations and tools, or other characteristics. This process encompasses six generic steps (activities), which are shown as chevron arrows in Figure 12-1. Depending on the context, individual steps may vary in abstraction level, system aspects considered, notations and tools used. Effort spent on a step will vary depending on quality/suitability of inputs (box labelled “User needs, …”) and the degree of reuse (e.g. the “Define ontology” step may just refine or extend a pre-existing ontology).

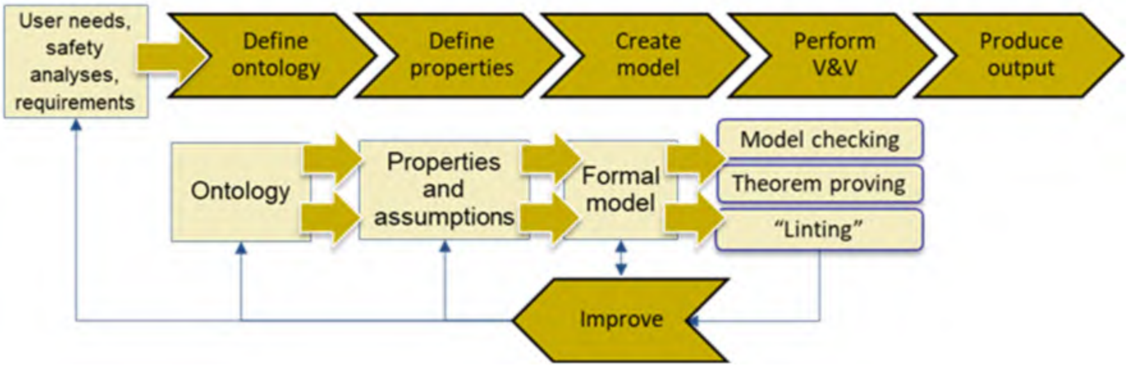


Figure 12-1: Generic process for FMs application

The following list briefly describes each step.

**Define ontology**. A conceptualisation of the domain structure which reflects the common view is defined, so that multiple stakeholders understand it in the same way. This includes relevant domain concepts, entities, ideas and their relations, which should be (a) well-chosen for the FM application purpose, as well as (b) sufficiently defined to be generally understood, and explicitly documented for later reference. Ontologies may range from a simple glossary to a formal ontology that allows automated reasoning.

**Define properties**. The relevant principles, requirements and assumptions for a system, its environment and its system parts are identified and defined in an informal language, using the concepts in the ontology. The aim is to formally prove the properties later and/or use them as part of such proofs. Various categories of properties exist, such as safety properties, environment assumptions, properties of configuration data, etc.

**Create model**. Some or all the defined properties are formalised in a chosen formal language to create a model. This may take the shape of a formal specification and/or a formal system model, and may be textual and/or graphical. The model can be created manually, or be automatically created (in whole or in part) by a tool from a specification, design, or implementation. Model creation should avoid unnecessary model complexity [11].

**Perform V&V**. The model is examined performing a range of verification and validation tasks such as manual review, simulation/testing, verification of mathematical consistency, generic and specific properties. Some of these tasks involve using formal techniques such as model checking, theorem proving or linting; some of them may require preparatory work such as the creation of configuration/test data or environment models.

**Improve**. Input material, ontology, properties, and model are adapted according to insights and learning, in particular from the two previous steps. This may include corrections, completions, but also improvements like simplifications, and may lead to iteration of previous steps.

**Produce output**. Depending on the FM application and the project context, artefacts for documentation (e.g. a V&V report), for later reuse (e.g. the model created) or as final result (e.g. improved requirements, implementation code generated from model) are produced or collected. Moreover, a successful FM application usually results in deeper knowledge for the (type of) system at hand, which may be incorporated in artefacts produced, distilled into guidelines or just remain as personal knowledge.

Finally, the guidebook points out and justifies that in general FMs work best when

- there is a clearly defined purpose (and system type) for the FM application and related best practices are followed,
- the scope includes the early stages of the system life cycle,
- staff possesses a complementary combination of skills, and
- learning from FMs application is reused “next time”.

### 12.3.8 Example FMs Application

WP10 of the X2Rail-5 project creates a FMs case study demonstrator based on the standard principles and requirements for ETCS Level 3 Trackside with Moving Block (L3 Trackside) [12], recently issued by WP4. The purpose is to perform V&V in the first life cycle phase HL1 (see Section “FMs in the system life cycle”), by applying the generic FMs process (see Section “Applying FMs”). The case study will be more extensively described in WP10 deliverables at the end of X2Rail-5, and relate to the recommendations, and general/specific techniques in the FMs guidebook. It corresponds to the System Inception purpose (see Section “Example purposes for using FMs”).

The case study considers L3 Trackside to be a self-contained subsystem with an event-based execution model. Compared to ETCS L2, a difference is that no interlocking subsystem is assumed (introducing an interlocking subsystem in the architecture “belongs to” the next high-level life cycle phase HL2). An event-based execution model was a natural choice to model the requirements in [12] for phase HL1. Events include ETCS messages (via radio), commands from traffic management, and status information from wayside objects (e.g., points, trackside train detection).

The ontology basis for the FMs demonstrator defines concepts in [12] as different types of objects, areas, and paths. Areas and paths are concepts that most people understand without difficulty, introduced to add more stringency (e.g., “Track Status Area” in [12] sometimes refers to an area, and sometimes to a path). A key concept of the ontology is the “dynamic path”, a path whose extent is determined dynamically. Dynamic paths are “first-class citizen” objects in the overall property-based reasoning for moving block requirements. The dynamic path concept itself is also relevant for FMs application and enables abstractions that are used, such as disregarding balise groups and actual distances in train position reports.

Properties defined for the case study include different types of assumptions (for adjacent systems, scope limitations, simplifying assumptions) and requirements that implementations of L3 Trackside shall satisfy. Formal verification is used for two complementary V&V purposes: (1) prove critical system properties, and (2) validate behaviour that the system allows. The latter is done by formal verification of dedicated properties, expressing that a sequence of system states / events is not reachable (is impossible). If such a property is proved true, then no sequence as specified is possible; if the property is falsifiable, the generated counter example illustrates a possible sequence. This type of properties is used to validate the behaviour. The following specific techniques (see end of Section "Understanding what FMs are") are used:

- Automated creation of a formal model (in the "High Level Language" HLL [13])
- Formal verification, with counter example generation (using a model checker for HLL)
- Visualisation of ontology concepts in counter examples, in a graphical track layout
- Debug capabilities, to isolate and understand the cause of a dynamic situation involving the properties defined

From the point of view of using FMs, defining properties and performing V&V for the case study does not present any principal technical challenges. The main challenges relate to that [12] provides a partial view of L3 Trackside requirements, as it builds on L2, and non-harmonised operational procedures (e.g. Shunting, Staff Responsible mode), requiring domain expertise. For this reason, learning about ETCS (to a degree) was required. Even so, informal property-based reasoning by FMs practitioners (using earlier versions of [12]) raised relevant questions for a small number of question & answer sessions with authors. Already this informal reasoning helped improve the quality of requirements, matching previous experience on FMs benefits [10]; it leads to increased quality at requirement stage, which is a big positive effect, as requirements issues are cheaper to address at this stage, and because the reuse factor is the largest (cf. HL1 in Table 12-2).

To what extent FMs-based V&V in the demonstrator that WP10 works on can help improve quality of requirements further, remains to be evaluated (work in progress at the time of writing).

## 12.4 Summary, Conclusions and Outlook

Shift2Rail TD2.7 decided to structure the guidebook based on describing:

- The generic life cycle phases that are relevant for FMs application, and the opportunities and recommendations for FMs use in each of them.
- The importance of having a clearly defined purpose for using FMs in a project and of making informed decisions when planning FMs use for that purpose (e.g., staffing, picking FMs, processes, tools, …).
- The generic FMs application process (independent of life cycle phase, specific FMs languages and tools used), in terms of its steps (activities).
- Recommendations and guidance for FMs application, for some typical purposes. Recommendations relate to the life cycle phases and the generic FMs application process, focused on being "FMs-friendly".

Some conclusions from work on the guidebook are that

- production of the guidebook was not an easy task; many discussions on FMs topics were held, such as on the purpose of using FMs, the benefits attainable and different styles and processes in using FMs (in the past, and for foreseeable future). A common view had to be agreed while personal backgrounds varied (expectations on, attitude towards, knowledge of, experience with and preferences for FMs).
- even though FMs have been used extensively for railway signalling in the past, there is a lack of reference structure to categorise different projects applying FMs, enable comparison of them and to better understand them in terms of the generic FMs application process. This may be a gap that the guidebook aims to fill.
- there is a general need for case study descriptions of projects that have used FMs, in terms of the guidebook structure and vocabulary. Describing representative FM applications in the guidebook would have required more resources than available (and bear the risk of becoming outdated).
- most known industrial projects using FMs in the past have related to phases HL3 and HL4, or from HL1 through HL4. Even though many have been successful (you always find errors if you perform formal verification), more benefits due to FMs seem possible by focussing on HL1 – to achieve high-quality requirements – as well as HL2 – to achieve compliant system architectures.
- the need for FMs experts will remain despite the guidebook (just like in any engineering discipline). The guidebook hopefully enables fruitful communication with FMs experts, but cannot fully replace expert judgement in specific project situations e.g. regarding suitability of a particular FM or tool, analysis of the impact of project decisions, resolving of conflicting requirements on FMs application, and understanding FM results in depth.

The guidebook is currently being completed and will be made publicly available on X2Rail-5 project website [14]. It will contain more details than could be included in the current extended abstract. As the guidebook does not provide case study reports on FMs use, WP10 aims to describe its ongoing moving block case study in terms of the guidebook structure in upcoming project deliverables, beyond what has been presented in Section "Example FMs Application", thereby validating the guidebook concepts. Any feedback on the guidebook creation and contents to the authors of the extended abstract or to the Shift2Rail TD2.7 group would be welcome.

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## 12.7 Authors

**Daniel Schwencke** graduated in Computer Science and received his PhD from the Technical University of Braunschweig. In 2011 he joined the DLR Institute of Transportation Systems as researcher, working in the field of railway safety, including system development and authorisation processes as well as human reliability. Since 2015 he is part of the verification and validation department, conducting research on model-based testing of signalling systems and test automation. He is involved in the European X2Rail-5 and R2DATO projects.

E-Mail: daniel.schwencke@dlr.de

**Arne Borälv** studied Computer Science at Uppsala University 1991-1995 and joined Prover Technology in 1995 and has worked on industrial application of formal verification since then, including in railways, automotive, avionics, and electronic design automation (EDA). He is involved in R&D within the European X2Rail-5 and R2DATO projects on behalf of Trafikverket (The Swedish Transport Administration).

E-Mail: arne.boralv@prover.com

**Fernando Mejia** graduated in Computer Science and received his PhD from the Paris University in 1982. He has worked on the industrial application of formal methods since then. First for electronic and computer manufacturers, and then, for 30 years for Alstom, a railway signalling manufacturer. He is involved in the European X2Rail-5 project as an independent consultant for Alstom.

E-Mail: fernando.mejia-ext@alstomgroup.com

# 13 Fail-Safe Train Positioning: Key Performance Indicators and Analysis Tools

*Terri Richardson, Michael Hutchinson; GMV-UK, Nottingham, United Kingdom*
*Paul Zabalegui Landa, Gorka de Miguel Aramburu, David Izquierdo Calzada;*
*CEIT, Donostia / San Sebastián, Guipúzcoa, Spain*

## 13.1 Introduction

In the frame of Shift2Rail TD2.4, i.e. Fail-Safe Train Positioning, WP6 of the X2Rail-5 project is aimed at developing technological demonstrators which are able to prove the feasibility of Virtual Balise (VB) detection by combining the state-of-the-art in satellite positioning, augmentation networks and kinematic sensor technologies. WP6 will produce three different demonstrators with related testbeds. A means of analysing performance in a consistent way across the demonstrators are required to allow for a meaningful and fair comparison.

## 13.2 Performance Indicators

In the context of GNSS, Key Performance Indicators (KPIs) and Performance Indicators (PIs) are used to measure the performance of a GNSS system. KPIs are typically more specific and focused on achieving system objectives, while PIs are more general and can be used to track a wider range of factors. It is important to note that there may be some overlap between KPIs and PIs i.e. some metrics may fall into both categories. By tracking KPIs and PIs, GNSS system operators and manufacturers can ensure that their systems perform as intended e.g. in terms of accuracy, reliability, and availability.

PIs are required that are suitable to assess the:

i) performances of the estimated PVT (Position, Velocity, Time) solutions and/or VB detection within the demonstrators.

ii) GNSS environmental conditions affecting the solutions.

In order to achieve this it is practical to define PIs in terms of the domains of measurements, PVT solutions and VB detection.

For each PI defined, different statistics may be computed to assess performance over time. Similarly, different plots may be generated depending on the nature of the PI. Examples of each are given below.

Statistics:

- Mean
- Standard Deviation
- Root Mean Square (RMS)
- Percentiles (50th, 68th, 95th, 99th, 99.9th etc)
- Minimum
- Maximum
- Availability (of the KPI with respect to a defined threshold)

Plots:

- Time series
- Histogram
- Cumulative distribution

### 13.2.1 Measurement Domain PIs

The focus in this section is on GNSS measurements, based on the expertise and project role of the authors. PIs for other sensors may also be pertinent. The following categories have been used:

*Measurement Availability*: PIs have been defined for pseudoranges, carrier phase and Doppler. PIs consider the number of satellites available from the different constellations used and the different signals of applicability.

*Measurement Quality*: PIs have been defined as related to the quality of individual measurements in terms of Signal-to-Noise Ratio (SNR), pseudorange multipath, presence of cycle slips and impact of cycle slips. Then, considering all measurements used and the resultant GNSS satellite geometry, the following Dilution Of Precision (DOP) PIs have been proposed: 3D Position Dilution Of Precision (PDOP), 2D Horizontal DOP (HDOP), Vertical DOP (VDOP), and Along-Track DOP (ATDOP).

*Measurements Used*: regarding the final PVT solution, PIs have been defined related to the number of satellites used (in total and for each constellation), and then the number detected as being faulty and the number excluded (both for all mitigation techniques combined and for individual mitigation techniques).

### 13.2.2 PVT Domain PIs

In the PVT domain, the following categories have been used:

*Accuracy*: determined by comparing a solution against the corresponding ground truth value at each epoch during the period analysed in order to generate a series of errors. Accuracy may then be computed based on the behaviour of these errors over the analysis period. PIs are defined in different dimensions for position and velocity (3D, 2D horizontal, 1D along-track).

*Availability*: based on solution availability, rather than service availability due to the absence of clear requirements. Solution availability is computed based on the number of epochs out of the total number analysed, at which a solution is available, regardless of its performance. PIs are defined for position and velocity (3D, 2D horizontal, 1D along-track).

*Integrity*: this is the measure of trust that can be placed in the correctness of the information supplied by a navigation system. Integrity includes the ability of the system to provide timely warnings to users when the system should not be used for navigation [1]. The following concepts are typically used to define and specify navigation integrity in the context of GNSS: alert limit, time to alert, integrity risk and protection level. However, these concepts aren't necessarily applicable in the context of railway signalling applications, in particular that of alert limit since any upper bound on a protection level and ultimately the train confidence interval is only relevant to operations and not safety [2]. The concept of protection level is retained as a means of computing an upper bound on the position solution for input to the train confidence interval. Tolerable Hazard Rate (THR) has analogies with integrity risk. Safe positioning must be prompt (equivalent to a time to alert of zero), however when using GNSS augmentation systems a non-zero time to alert is inherently imposed and must be managed.

With this in mind, the following two integrity PIs are applicable to the VB application:

- Probability of Misleading Information: a misleading information event occurs when the position error exceeds the protection level. A probability may be derived from the number of such events that occur over the analysis period, and compared against the applicable THR requirement.
- Availability of Integrity: determined based on the magnitude of a protection level (xPL) when compared against a threshold of relevance to the application. It is computed based on the number of epochs out of the total number analysed, at which the xPL is below the threshold.

### 13.2.3 VB Detection PIs

VB detection PIs have also been defined by members of the project consortium from the railway signalling industry (not reported in this abstract).

## 13.3 Performance Analysis Tool

A performance analysis tool is proposed for the visualization and evaluation of the measured data and computed PVT solution. This tool has been developed in the frame of WP6 of the X2Rail-5 project [3] as a complementary work to the train integrity simulator developed in X2Rail-4 WP6 and WP7, and both are part of the developed Railway Advanced Navigation Simulation and Evaluation System (RANSS) (see Figure 13-1).

The main purpose of this performance analysis tool is to apply and calculate the different performance indicators discussed in Section 2 in order to evaluate the quality of the PVT solution against ground truth measurements and the quality of the measured data in order to detect the existence of outliers that may degrade the performance of the said solution.

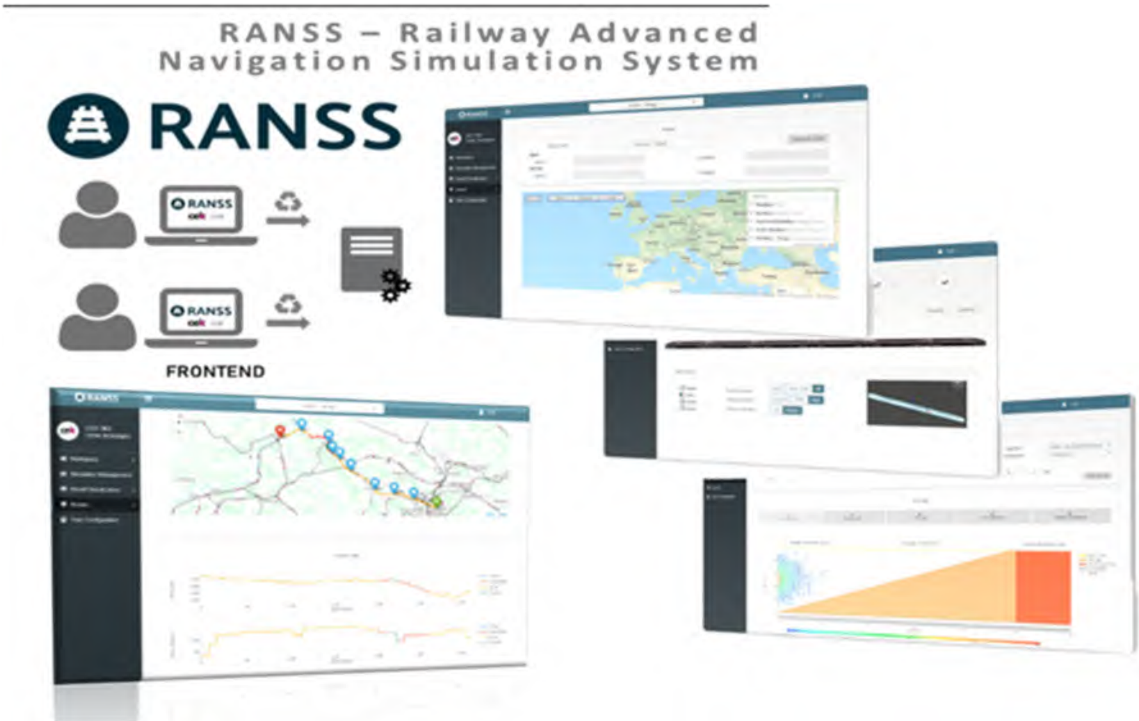


Figure 13-1: RANSS environment.

Accordingly, the developed tool is formed by three different modules, each of them aligned with the previously mentioned sections:

- Raw-data evaluation

  This first module has been designed to load, read and analyze the raw data recorded during measurement campaigns with multisensor navigation systems. For the time being, it has been focused on data corresponding to GNSS (in RINEX format), Inertial Measurement Units (IMU) in a proprietary format and UWB range data in Decawave's proprietary format [4].

  This module can be especially useful to compare raw data and preprocessed data and analysing the performance of the preprocessing algorithms, which can solve errors such as

  1. Ionosphere delay, which results from the signal travelling through the ionosphere and causes a delay in the signal that is frequency dependent. This error can be corrected using ionosphere models or dual-frequency measurements.

2. Troposphere delay, which results from the signal travelling through the troposphere and can be corrected using troposphere models.

3. Receiver clock errors, which occur due to inaccuracies in the receiver clock, can also cause errors in pseudorange measurements and can be corrected by using a network of receivers or by using a reference station.

4. Ephemeris errors, which result from inaccuracies in the satellite position and clock, can cause errors in pseudorange measurements and can be corrected by using precise ephemeris information.

5. Multipath, which results from inaccuracies in the satellite position and clock, can cause errors in pseudorange measurements and can be corrected by using precise ephemeris information.

- Evaluation of the PVT solution

  This second module has been designed to qualitatively analyze the computed results and check the behaviour of these (see Figure 13-2). For this purpose, it plots the PVT solution in terms of:

  1. Coordinates over Cartesian axis and maps.
  2. Velocity profile over time.
  3. Number of employed satellites over time for the computation of the PVT solution.
  4. Dilution of precision (DOP) over time, which represents the error propagation as a mathematical effect of the navigation satellite geometry on positional measurement.

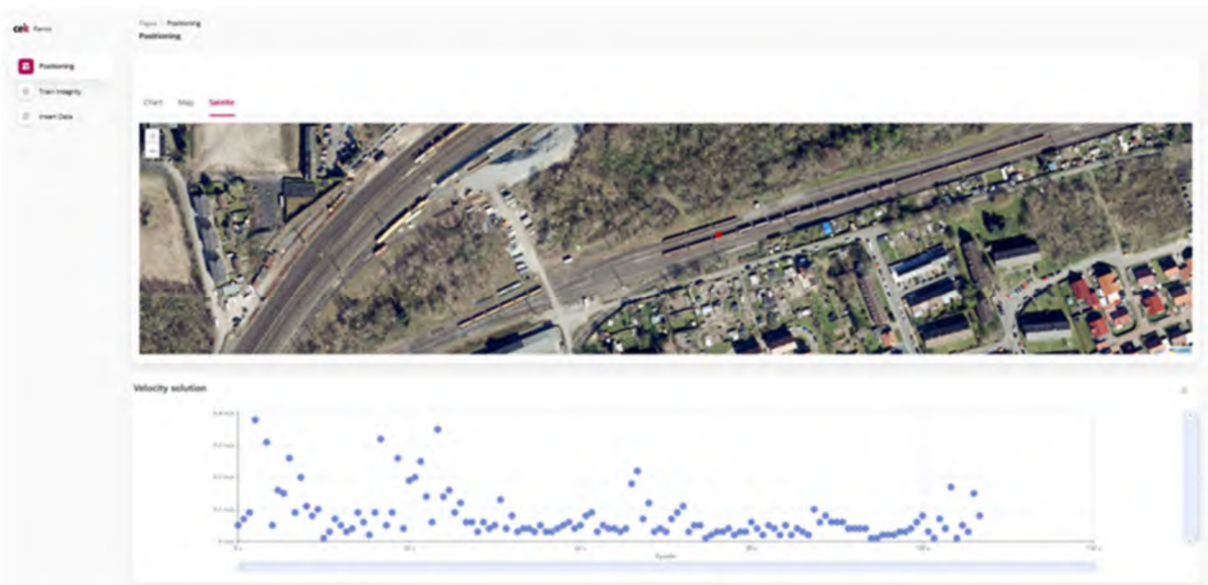

Figure 13-2: RANSS - Example of the PVT solution-related plots.

- Performance analysis of the PVT solution

  This third module compares the computed PVT solution against a ground truth reference in order to analyze the quality of its performance. This is done by referencing each of the computed PVT solution epochs with the closest in time of these forming the ground truth. This error curve is broken down into a horizontal positioning error (HPE) and a vertical positioning error (VPE).

  For each of these curves, different performance indicators are applied (see Figure 13-3), so that a deep analysis can be performed in terms of accuracy, availability and integrity. The accuracy-related analysis is done by applying the statistics shown in Section 2.

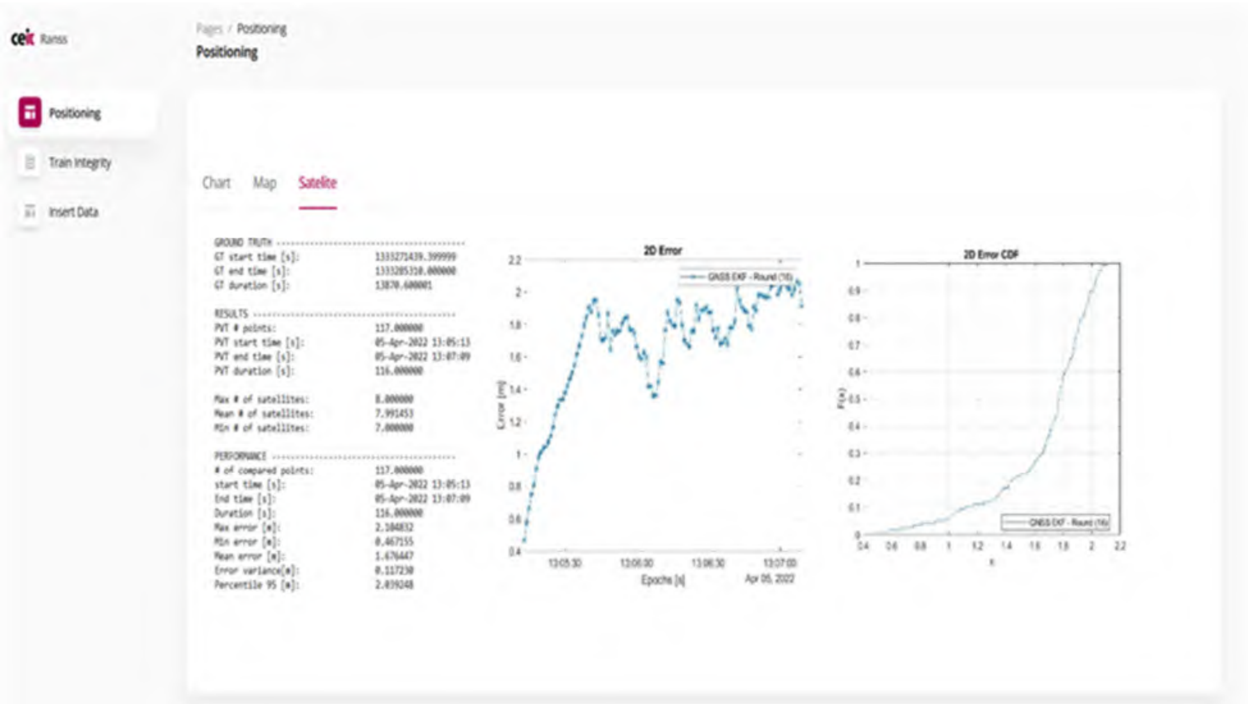


Figure 13-3: RANSS - Example of the plots related to the performance of the positioning algorithm.

## 13.4 Conclusions

The performance analysis of navigation algorithms allows the evaluation of multiple aspects of the quality of said algorithms. With the aim of proving the feasibility of Virtual Balise (VB) detection based on state-of-the-art satellite positioning, and evaluating the three different demonstrators with related testbeds, a tool for analysing performance in a consistent way across the demonstrators has been proposed which allows a meaningful and fair comparison. For this purpose, this tool employs a wide variety of performance indicators to evaluate the quality of the mentioned algorithms in terms of accuracy, availability and integrity. The continuation of this study will be focused on finding more Performance Indicators to characterize and analyse the performance of navigation systems and analysing the currently existing navigation systems, which may be presented in some Flagship Areas (FA2 [5] and FA6 [6]) of the upcoming European initiative Europe's Rail Joint Undertaking (EU-Rail).

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European Union Funding
for Research & Innovation


## 13.7 Authors

**Terri Richardson** is a Senior Navigation Engineer at GMV, where she works on GNSS integrity for user applications. She received a B.Sc. and M.Phil. in Surveying and Land Information from the University of the West Indies and a PhD in Civil Engineering and Geodetic Science from The Ohio State University (USA).

E-Mail: terri.richardson@gmv.com

**Michael Hutchinson** is the GMV-UK International Business Development Manager. He has an engineering background in GNSS and PNT technology, with considerable experience in developing applications and solutions for the railway sector for industrial and institutional customers in the UK and Europe. He holds an MSC in Satellite Positioning Technology from the University of Nottingham.

E-Mail: michael.hutchinson@gmv.com

**Paul Zabalegui Landa** received his M.Sc. and PhD degrees in Telecommunication Engineering from TECNUN (University of Navarra, San Sebastián, Spain) in 2018 and 2022 respectively. Nowadays, he is at CEIT-BRTA, in San Sebastián (Spain) where his research interests include satellite positioning technologies and transportation signalling systems.

E-Mail: pzabalegui@ceit.es

**Gorka de Miguel** received the M.Sc. degree in telecommunications engineering from TECNUN (School of Engineering of San Sebastián), University of Navarra, Donostia-San Sebastián, Spain, in 2015. In 2015, he joined the CEIT-BRTA Research Centre, Donostia-San Sebastián, Spain, where he is currently a Research Assistant and a PhD student within the Transport and Sustainable Mobility Group. He is also an Assistant Lecturer in Electronic Fabrication Systems with TECNUN. His research interests include the field of EU and software development. He is now actively participating in H2020 European funded projects in Railway signaling and positioning topics.

E-Mail: gdemiguel@ceit.es

**David Izquierdo** received a degree in web and multiplatform applications from Plaiaundi, Spain, in 2020. He joined the CEIT Research Center in San Sebastián in 2020 and is currently a Research Assistant in the Department of Transport. and Sustainable Mobility Group. His research activity is situated in the field of web and mobile software development. Now he actively participates in projects financed with European H2020 funds on railway signaling and positioning issues.

E-Mail: dizquierdoc@ceit.es

# 14 Ground truth and validation tools for the development of on-board railway positioning systems

*Paul Zabalegui Landa, Gorka de Miguel Aramburu, David Izquierdo Calzada, Iñigo Adin Marcos, Jaizki Mendizabal Samper; CEIT, Donostia / San Sebastián, Guipúzcoa, Spain*

## 14.1 Introduction

Currently, railway sector aims at relying at on-board positioning system for a number of functions, including safety-critical functions as part of the technological evolution of the sector. Therefore, a number of research projects in Europe are aiming to move towards finding the most relevant strategies and solutions. These projects tackle the positioning problem in many different ways, offering more than one solution. However, there is the issue of assessing the performance of the proposed on-board positioning solution.

This abstract aims to target the on-board positioning performance assessment in order to reinforce the need of defining a common procedure to be followed by all the railway community. First of all, the objective of the positioning system and its outcomes are presented. Secondly, the methodology to obtain the Ground Truth as the referent to compare the results obtained from the system is included. After that, the validation tool where the results are visualized for the performance evaluation is shown. Finally, conclusions of the works are drawn.

## 14.2 On-board positioning system

In order to obtain the performance of the on-board positioning systems, its end-user requirements shall be translated to measurable KPI related with the position, such us: availability, accuracy, integrity with additional statistical figures [1]. This leads to analyse the outcome of the on-board positioning system obtained by means of the measurable KPIs defined. For that, the need is twofold; On one hand, there is a need for a reliable and faithful reference (Ground Truth) to compare the outcomes of the system [2] and on the other hand, a tool to compare those results is required [3].

For the first issue, one of the most used solution is to use a high-end positioning system which usually uses the same input data as the one that is under test (lower grade). In this situation, it seems to be difficult to ensure the independence of the data. And, therefore, same issues could shadow reality in both systems. Maps can be used to solve this issue. For that, maps have to be digitalized and converted into a proper format and coordinates to facilitate the comparison labour. However, maps only offer static information, this means that only a position is provided and there is no timestamp to be used to determine when the given position happened. Thus, comparisons are done by taking the closest point to the estimated position.

But then, what if the position estimation has a position drift? This way of comparing the data will mask the error obtaining misleading results.

And last but not least, can these results be extrapolated to other environments? The answer is complex as the environment is also complex and particular to each of the lines, orography, weather conditions, etc.

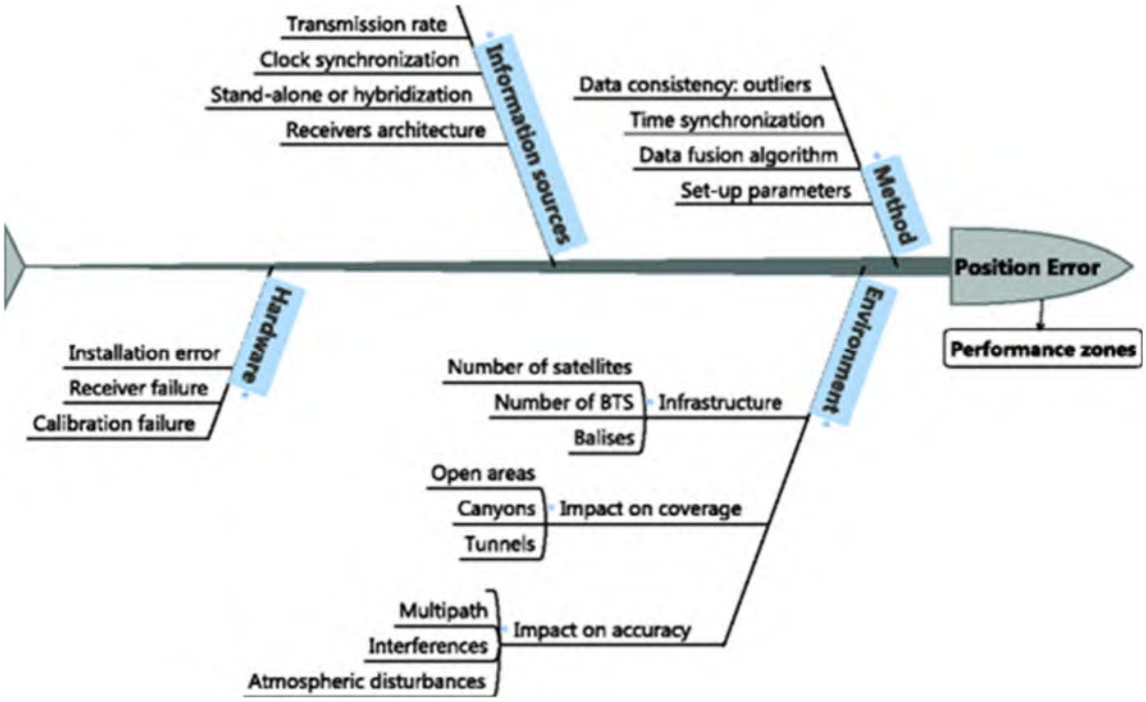


Figure 14-1: Effects contribution to the error of the position estimation [2]

Then, the most important point is, how can we deal with all these open points? Next section proposes one approach that could diminish the impact and provide a common alternative to start facing some of the presented problems while measuring the performance of the on-board positioning systems.

The main distinction of the use of the position relies on the final purpose of the obtained information. In this case the focus is settled only in those cases where the unreliable position information could cause severe hazards on the operation or even worse, accident involving human fatalities. Railway sector already ranks this kind of risk defining a safety integrity level, which links the frequency in which the system/information is used, the probability of having misleading information and the consequences. Then the discussion should be moved towards which is the SIL that the on-board positioning systems should have and if it is feasible to reach a SIL4 solution.

This decision already defines procedures related with the implementation of the final system, from all the points of view, electrical compatibility, software design and even a full system life-cycle specification. Based on the SIL defined, the processes face more tight and tedious procedures in order to ensure that the SIL is meet.

Even if the selection of a SIL level is complex the trend and needs of the railway sector are leading to have at least a level greater or equal to two. Now once a SIL level is defined, the next point is to move to the definition of the requirements. It should be something easy to tackle but, railway operators, infrastructure managers and developers have different KPIs as objectives, making it difficult to translate and evaluate which is the impact of having a translation, for example, between the accuracy and the capacity enhancement that produces.

## 14.3 Ground Truth (GT)

First, it is important to highlight that the performance evaluation of a railway navigation must be carried out by the comparison of the position, speed or other information between the computed information and the reference ground truth. This is the analyzed option in this document as the internals of each demonstrator are now known. Thus, this comparison is carried out by having a time referenced measurement for the information. This allows a straight comparison in time without any need for position interpolation in case the times are matched, and measurements are perfectly synchronized. In case synchronization is not available, the ground truth must be of higher frequency to reduce the error introduced by the position interpolation. In case of a constant time offset between the ground truth and the measurements, an error in the synchronization can be assumed and the time reference can be corrected.

Second, the accuracy of the measurements regarding the information to generate the ground truth must be ensured. This means that the ground truth must be obtained with systems of higher accuracy grade than the PVT measures under test, and the technologies used for the generation of the GT must be ideally different and/or employ high-end systems and as an optimum, using other physical principles and technologies to avoid errors were both measures are affected the same way. Ensuring the resilience and accuracy of the generated ground truth.

Different alternatives for generating the ground truth are possible, the first point is based on the absolute and relative measures. The most common technologies are based on position trilateration, detection of fixed and referenced position marks, and travelled distance calculation between points.

- Trilateration technologies:
  - GNSS – Global Navigation Satellite System
  - UWB – Ultra-WideBand
- References position marks
  - RFID – RadioFrequency IDentifiers
  - Balise
  - Optical marks
- Travelled distance
  - Odometer
  - IMU (by double integration) – Inertial Measurement Units

As mentioned, to have a reference the use one of these technologies or a combination of them must be used. The performance of each of the technologies is related also to the cost of the solution. Higher-end systems will provide more reliable and accurate solutions as the errors, biases or negative side-effects are reduced or countermeasures are applied.

In addition to this, the need to install the necessary infrastructure for some of these technologies can be seen as the main drawback. This means that apart from the onboard equipment installed to gather the information, additional equipment must be installed along the track (See Table 14-1).

Analyzing the availability of the measurements standalone systems are independent and could provide measurements independently of the environment. Besides, the rest of the technologies where the limitation of the infrastructure installation and/or the environment (tunnels), could limit the availability significantly.

Regarding the performance, it depends on the cost of the solution as higher-grade systems have better performance characteristics, however, systems where the infrastructure is controlled and the environment does not affect the measurements provide enough accuracy to even be capable of identifying parallel track scenarios.

GNSS can be used in different manners and depending on it, different accuracy can be reached. For instance, GNSS standalone have different accuracy ranges as multi-constellation and multi-frequency approaches reduce the impact of the error and can provide performances between 1-5 meters in open sky conditions. In the same way, when using GNSS with additional infrastructure deployment, and augmentation stations, the accuracy performance can be reduced to the submeter level. The drawback of this solution is the need to deploy augmentation stations to provide the corrections to the rover (in this case the train that generates the ground truth). The GNSS PPP solutions could increase the accuracy, but this method needs to converge to give such accuracies, which in dynamic scenarios is more complex to achieve and not in real time, for now.

UWB technology requires the installation of so-called anchors, ideally in a square mesh layout. Each anchor's action range may vary up to 50 meters of distance, depending on the environment. This means that the number of anchors needed to cover a track makes the solution less scalable, compared to GNSS. However, accuracies reached with this technology are around 15-50 cm.

Similarly, reference position solutions, provide a high accuracy but also the need for deployment along the track. In this case, the coverage is reduced, but the need for only one anchor per point can reduce the cost of the installation. Moreover, due to the limited range of these systems, the accuracy may vary between centimeters (RFID, optical marks) to meters (balise). The higher definition of the ground truth produces a higher deployment need and consequently a higher cost.

Distance-based solutions have the main issue, regarding the accuracy, that the error drift increases with time (considering that a reset of the error is not carried out). Additionally, the higher the cost the lower the errors and the higher the accuracy.

Table 14-1: Technologies for ground truth generation

| Technology | Type | Infrastructure | Availability | Performance | Scalability |
|---|---|---|---|---|---|
| GNSS | trilateration | Yes | 3/4 | 4/5 | 5 |
| UWB | trilateration | Yes | 4 | 5 | 3 |
| RFID | Ref. position | Yes | 4 | 5 | 4 |
| Balise | Ref. position | Yes | 5 | 2 | 2 |
| Optical marks | Ref. position | Yes | 4 | 5 | 4 |
| Odometer | distance | No | 5 | 3/4 | 5 |
| IMU | distance | No | 5 | 4 | 5 |

Having said that, the need to combine different technologies is a must for the ground truth generation. Additionally, the combination of standalone and non-standalone solutions is also a must for railway environments where the lack of coverage is an issue that the system will be facing. Depending on the expected lack of coverage and the accuracy of the standalone solutions, the most common solutions are the combination of GNSS, IMU and odometer. Higher-grade systems are used for the ground truth generation compared to the fail-safe positioning systems due to the cost factor of installing high-cost equipment on every train. This reduces the independence between the technologies used but reaches a trade-off regarding the expected capabilities and cost. For smaller tracks or test areas where high precision is needed, for instance in the hundreds of meters order of magnitude, reference position markers could be an option. Though it is important also to consider the cost of the deployment time, it may vary from system to system.

Once this is understood each company usually generates the ground truth according to the information available and the track under test, so, this information may differ from demonstrator to demonstrator, but there are a set of common fields that are included in all of them. This analysis focuses on the need of defining these common fields and provides standardization of those fields considering the units and format provided.

## 14.4 Ground Truth file format

The goal of this publication is to propose Ground Truth suitable to reflect accurately the real behavior of the system under test by providing a reference trajectory. This GT information is also an estimation, but as no better information is gathered, it will be considered as a reference. In this section, the requirements for a valid ground truth are presented and in addition to a proposal of GT file format capable of handling any further GT improvement by extending the basic common part of the GT file with optionally enriched further company-specific parameters.

Regarding the format, the binary format although is the most size efficient, it has two main disadvantages: The first one is the reduction of the flexibility of the file and the second one: the information is not human readable. To achieve a trade-off, a comma-separated (CSV) file is going to be generated with some guidelines where companies can include information not common to the defined basic format.

The file is divided into 3 blocks (starting with ###, which are params, comments and data) and the data is divided into four sections. First, the common parameters that are needed to understand and describe the file. Afterwards, the optional/specific comments of the different developers (red). Then in the data block a header line, where the description of the column with its unit is defined and finally the lines of data values. Thanks to the nature of the comma-separated values (CSV) after a certain agreed number of common columns (blue), the rest of the columns that are for vendor purposes (red) will be ignored. The analysis of the optional data is carried out by the vendor. In this manner, the defined file format does not limit any possibility, and anybody could have internal specific data for the analysis without interfering with the use of more automated tools to obtain the agreed figures of merit and indicators.

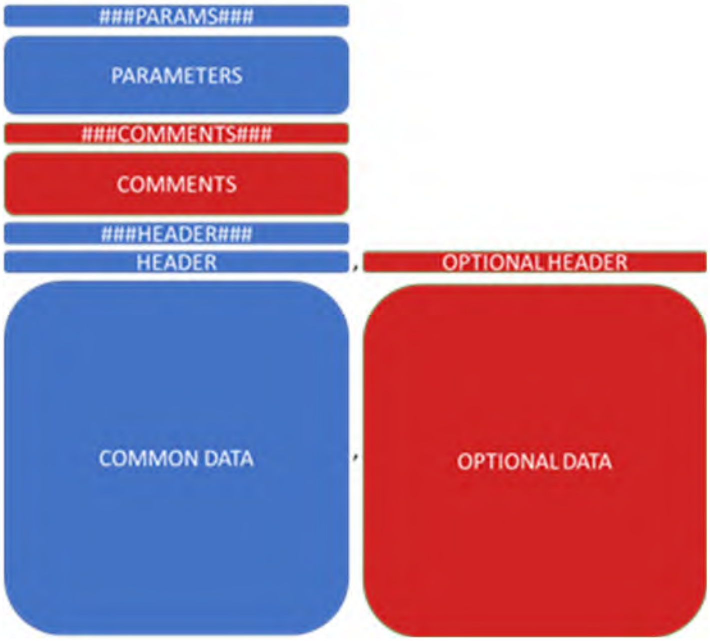


Figure 14-2: Structure of GT data in a common file

## 14.5 Parameters of the GT File

The parameters of the GT files are described as follows:

- TYPE: Codified value to cover the different approaches, such as different X2R5 streams. It is defined as 2 digits (2x) XX.YY. The first two digits defined the stream (00 Continuous Positioning and 01 VB) and the second pair of digits was the company code. (00-CEIT, 01-CAF, 02-HSTS, 03-AZD, 04-MERMEC, etc.). Based on this code parser can be adjusted to understand the specific columns that could be apart from the required minimum.
- DATE: Date and time of the measurement in human-readable format (YYYY/MM/DD HH:mm:SS.FFF)
- NAME: Descriptive ground truth name, recommended to use the start station and end station, even if the measurements are carried out in between and do not start or end in the station.
- FREQ: Frequency of the ground truth information data, e.g., 1000Hz

### 14.5.1 Data specification

In this section, the required information used for the ground truth is specified in Table 14-2 and detailed below.

Table 14-2 Required minimum fields specifications

| **Column** | **#1** | **#2, #3, #4** | **#5, #6, #7** | **#8** | **#9** | **#10** | **#11** |
|---|---|---|---|---|---|---|---|
| Parameter | GPST or UTC | XYZ ECEF coordinates in ITRF frame | X, Y, Z uncer-tainties | Actual speed (Norm of the 3D) | Speed uncertainty | Travelled distance | Indicator of absolute '1' and relative '0' references |
| Unit | [s] | [m] | [m] | [$ms^{-1}$] | [$ms^{-1}$] | [m] | [-] |
| Resolution | 0.001 s | 0.001 m | 0.001 m | 0.01 $ms^{-1}$ | 0.01 $ms^{-1}$ | 0.001 m | [-] |

1. The first column in the reference data file has to be the time reference, due to the different demonstrator two alternatives are viable as long as the format is followed all the time. The first alternative is the use GPST in the format which was defined one number which equals to FullGPSweek*604800s + SecOfWeek. The other alternative is providing the UTC date and time as a string (dd/mm/yyyy HH:MM:SS.sss) or a a numerics representation by converting each field to milliseconds and adding them.

2. XYZ ECEF coordinates of the reference position of the GNSS antenna have to be specified in the ITRF frame. It is strongly recommended to check the coordinates of geodetic data (i.e. data of track axis) because the XYZ coordinates of geodetic data are usually stored in the ETRF frame, not in the ITRF frame (and WGS84 datum). ETRF is considered for surveying measurements in the EU because the data in ETRF are fixed with Eurasian Plate. To be Ground Truth data usable for further processing, their x, y, and z coordinates have to be in ECEF, in the ITRF frame (ITRF2008 or later realization). In general, ITRF is identical to WGS84 at a one-meter level, but the latest realizations of ITRF2008, ITRF20014 and WGS84 (G1674) are likely to agree at the centimeter level. The transformation of ETRF coordinates into ITRF coordinates is not trivial, so it's recommended to ask the provider of geodetic data of the track axis for the data in the proper coordinate system (ECEF, ITFR2008 or ITRF2014).

3. XYZ ECEF uncertainties of the position estimate of the ground truth.

4. Actual speed refers to be an absolute value of the train speed.

5. Speed uncertainty of the actual speed.

6. Indicator of absolute and relative information shows by a simple integer value of '1' if a reference point (e.g. balise, RFID tag, etc.) has been detected at this time or if the data is post-processed calculated relative positioning.

### 14.5.2 Ground Truth example

This paragraph presents an example of the file containing all the above-mentioned information, and the included specific information is highlighted in red.

Table 14-3 Ground Truth file example

```
###PARAMS###

TYPE: 00.00

DATE: 2021/10/26 18:46:40 Generation date of the file (or of the GT recording start?)

NAME: Easo – Anoeta

TIME_REF: GPST #GPST or UTC

FREQ: 1000Hz

DELIMITER: ,

DECIMAL_SEPARATOR: .

###COMMENTS###

Ground truth generated for the X2R5 test campaign.

Train: UT200

Technologies: GNSS, IMU, LIDAR, RFID Tag

GNSS: GPS L1, L2 + Galielo E1,E5 (RTK mode)

Configuration: RTK mode

IMU: 16g @1000Hz

###HEADER###

GPST(s), X(m), Y(m), Z(m), Xu(m), Yu(m), Zu(m), V(m/s), Vu(m/s), Travelled distance (m), Abs Ref Balise (Boolean-1/0), A(m/^2), XXXX

1319300487.230,4647155.054,-160940.303,4351152.472,2.01,1.87,0.75,8.01,0.25,0.001,0,0.04,XXX

1319300487.231,4647155.052,-160940.305,4351152.474,1.81,1.67,0.85,8.12,0.26,0.007,1,1.02,XXX............
```

## 14.6 Validation tool

The developed validation tool aims on evaluating the performance of a navigation solution against a trustworthy ground truth, which follows the format shown in Table 14-3. This is done by comparing each of the epochs of the solution file against the closest ground truth epoch, which is considered to be contemporary if the time difference between these two does not exceed the 0.05-second barrier. This comparison is performed by means of the differentiation in position and velocity between the solution epoch and the reference one, and the latter estimation of different statistics (see Figure 14-3) of this difference such as

- Mean
- Standard Deviation
- Variance
- Root Mean Square (RMS)
- Percentiles (50th, 68th, 95th, 99th, 99.9th etc)
- Minimum
- Maximum

x


Figure 14-3: Displayed statistics about the performance of the computed solution.

Moreover, for the sake of a better intuitive understanding, multiple plots are displayed. These plots show the behaviour of the computed difference (which is assumed to be the error between the solution's performance and the reality) by plotting different points of view of it. Figure 14-4 shows an example of the mentioned plots, where the HPE time series is first shown together with the solution's position so that the user can easily find any misbehaviour or outlier and locate it both in a certain location and at a specific epoch.

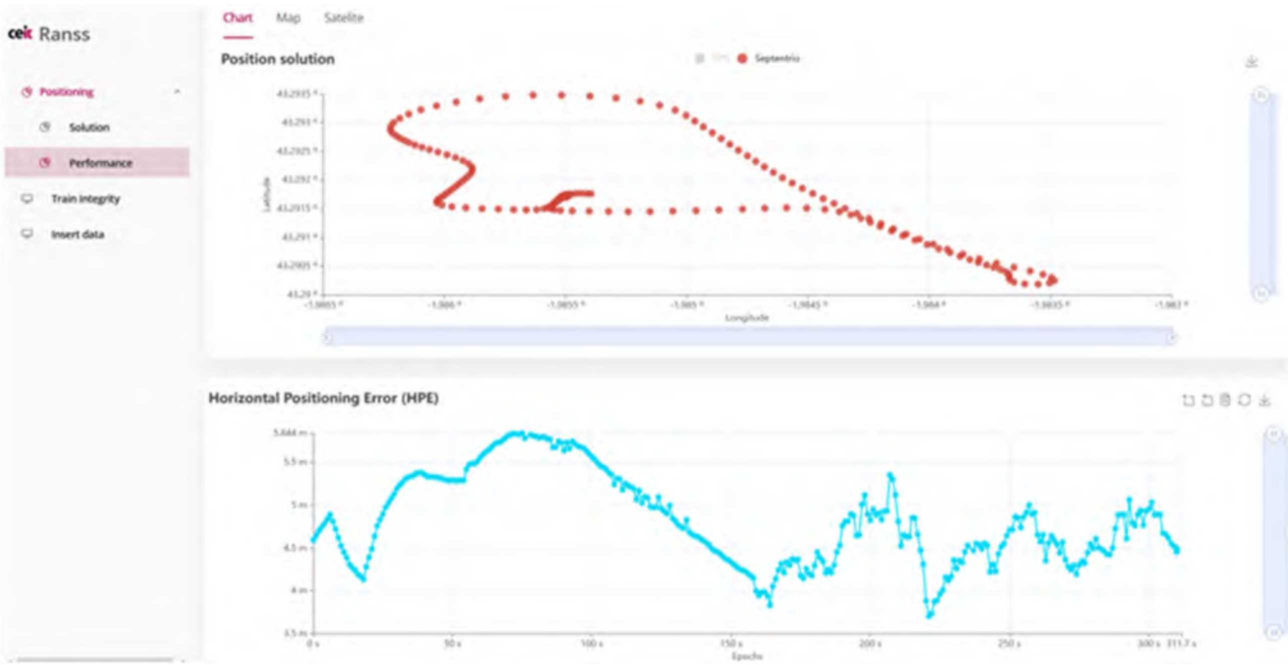

Figure 14-4: Front-End of the developed visualization tool.

Furthermore, a graphical representation of the solution's performance in terms of its integrity is also given. This is done in the form of a Stanford plot (Figure 14-5), which compares the, in this case, Horizontal Positioning Error (HPE) against an a priori error's upper bound known as the Horizontal Protection Level (HPL). This plot shows the integrity of each of the estimated solution epochs, declaring them valid to be used or raising Misleading Information (MI) events whenever the protection level turns out not to be an upper bound of the positioning error.

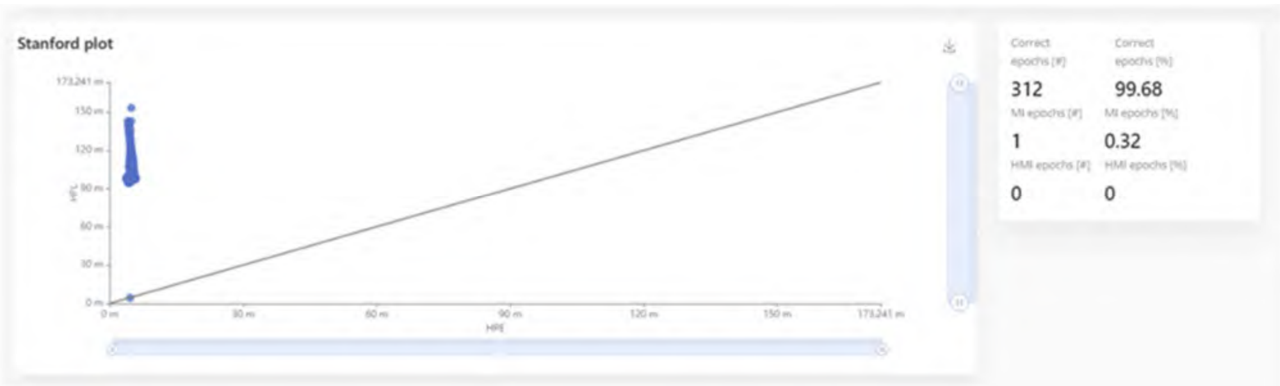


Figure 14-5: Stanford plot.

## 14.7 Conclusions

The analysis of the performance is an issue that the railway industry and the developers are facing. The need of having a reliable manner to quantify the performance of the on-board positioning systems is a priority. If there is no consensus on this point it will be impossible to move forward and use global positioning systems in order to get closer to the full autonomous train. The certification process has to cover all the possible issues that the on-board system could see in order to determine the safe behavior of it. The field-tests for this purpose will make the system certification a really expensive process and thus an extensive test list could not be carried out using this method. The why is clear, but the how must be answered. The proposed method mixes both worlds with the aim of reducing the certification cost by simulating most of the processes but also having a real field-test where the operational performance is also checked. Having proposed a method that helps to analyze the fault rate of an onboard navigation system, the path to the certification of said system and the achievement of said SIL level has been cleared. Accordingly, the continuation of this work will try to study and fulfil the safety requirements that a multisensor navigation system should contemplate during its performance.

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Disclaimer: This dissemination of results reflects only the authors’ view and the Shift2Rail Joint Undertaking is not responsible for any use that may be made of the information it contains.


## 14.10 Authors


**Paul Zabalegui Landa** received his M.Sc. and PhD degrees in Telecommunication Engineering from TECNUN (University of Navarra, San Sebastián, Spain) in 2018 and 2022 respectively. Nowadays, he is at CEIT-BRTA, in San Sebastián (Spain) where his research interests include satellite positioning technologies and transportation signalling systems.

E-Mail: pzabalegui@ceit.es

**Gorka de Miguel** received the M.Sc. degree in telecommunications engineering from TECNUN (School of Engineering of San Sebastián), University of Navarra, Donostia-San Sebastián, Spain, in 2015. In 2015, he joined the CEIT-BRTA Research Centre, Donostia-San Sebastián, Spain, where he is currently a Research Assistant and a PhD student within the Transport and Sustainable Mobility Group. He is also an Assistant Lecturer in Electronic Fabrication Systems with TECNUN. His research interests include the field of EU and software development. He is now actively participating in H2020 European funded projects in Railway signaling and positioning topics.

E-Mail: gdemiguel@ceit.es

**David Izquierdo** received a degree in web and multiplatform applications from Plaiaundi, Spain, in 2020. He joined the CEIT Research Center in San Sebastián in 2020 and is currently a Research Assistant in the Department of Transport. and Sustainable Mobility Group. His research activity is situated in the field of web and mobile software development. Now he actively participates in projects financed with European H2020 funds on railway signaling and positioning issues.

E-Mail: dizquierdoc@ceit.es

Dr. **Iñigo Adin** He received his M.Sc. Degree in Electronics Engineering in 2003 and his Ph.D. in 2007 from the University of Navarra. His research interests include safety-critical designs, with special interest in positioning, communications, electromagnetic compatibility and transport interoperability. He is author, or co-author, of four patents, 2 technical books, an invited chapter and 40 articles in journals and international conferences. He was the coordinator of the FP7 European Project TREND and H2020 AIOSAT for GSA. Moreover, he has participated in 5 projects from the Shift2Rail initiative and is now involved in 3 projects from EU Rail framework.

E-Mail: iadin@ceit.es

**Jaizki Mendizabal** received his M.Sc. and Ph.D. degrees in Electrical Engineering from TECNUN (University of Navarra, San Sebastián, Spain) in 2000 and 2006 respectively. He joined Fraunhofer Institut, Germany) and SANYO Electric Ltd, Japan as RF-IC designer. Nowadays, he is at CEIT BRTA, in San Sebastián (Spain) where his research interests include communications and electronic systems. He is lecturing "Communications Electronics" and "Communications via Radio" at TECNUN (University of Navarra).

E-Mail: jmendizabal@ceit.es

# 15 Splitting and connecting of railway infrastructure network representations: a railML case study

*Christian Rahmig, DLR, Institute of Transportation Systems, Braunschweig, Germany*
*Adam Hlubuček, Czech Technical University, Prague, Czech Republic*
*Larissa Zhuchyi, Ukrainian State University of Science and Technologies, Dnipro, Ukraine*
*Vasco-Paul Kolmorgen, RailML.org, Dresden, Germany*

## 15.1 Introduction

With respect to its digital representation the railway sector is currently acting in a fragmented way and in silos corresponding most often to physical or functional subsystems or use cases. Different institutions and stakeholders own and manage parts of the data e.g. of the overall railway infrastructure at regional or national level, which prevents having a global view or full control of the railway operations system. On the other side, data of big railway infrastructure network often need to be splitted into smaller fragments, e.g. for scaling of a construction site within a station or on a specific line section.

In that context, integration of data of railway infrastructure networks is not a completely new topic: The plan to create the Trans-European Transport Network was developed in 1990. At the level of information systems, this goal is achieved by data integration methods, such as common vocabulary for describing railway infrastructure and timetables. Later on, for technical realization of this plan, approaches towards seamless machine-readable & meaningful data exchange have been developed within the 4th Railway Package for the Single European Railway Area were developed. One of them is data FAIRification (Findability, Accessibility, Interoperability, and Reusability) [1]. In the railway context it can enhance planning transportation routes and construction projects as there are always a lot of parties involved

The aim of this paper is to investigate different approaches for splitting and integrating railway infrastructure network representations. In particular, the focus of research is on a case study using the standard railway data exchange format railML®.

This paper is organized as follows: Section 2 describes the state of the art introducing the modelling principles of railway data exchange format railML® and presenting existing possibilities of data integration. Based on this technical introduction section 3 states the problem to be investigated in this paper. The following sections 4 and 5 present two different, but complementary approaches towards splitting and integrating of railway infrastructure networks. Finally, section 6 concludes the paper and proposes perspectives for ongoing work.

## 15.2 State of the Art

The principles of splitting and connecting of railway infrastructure network representations presented in this paper will be demonstrated on a case study related to railML – an XML-based data format used for the exchange of data among railway software applications. Currently, the greatest emphasis is placed on railML version 3, which, as far as its infrastructure scheme is concerned, is based on the RailTopoModel principles and uses a use-case oriented approach for its incremental development. The latest version is railML 3.2, which has been released on April 26, 2022 [2] [3]. This version is based on an improved RailTopoModel version V1.4 [4].

The most developed layers (sometimes also referred to as views) of the raiML 3.2 infrastructure schema are the topological layer and the functional infrastructure layer, bound together by the <topology> and <functionalInfrastructure> elements, within a railML file [3]. The underlying topological layer, thoroughly expressed by the RailTopoModel, allows us to formalize aggregation of different levels of abstraction of the drivable railway network. The functional layer is used to represent detailed infrastructure objects such as balises, signals or switches, as well as aggregated infrastructure components, e.g. operational points etc. The generic RailTopoModel collectively calls them "net entities", sets common rules for their localization in relation to the topological layer net elements and used coordinate systems.

## 15.2.1 Topological Layer

The topological layer is the underlying layer of the railway infrastructure description used to anchor individual instances of specialized classes of net entities to it, using intrinsic coordinates or coordinates of individual defined coordinate systems. Most of the railML element types used to describe the topological layer are derived from the RailTopoModel. Their instances are individual <netElement> elements, which are the elements to which individual coordinate systems can be associated and to which net entities can be located. Further, there are <netRelation> elements which connect individual <netElement> elements to each other. Finally, the <network> elements represent complete sets of <netElement> and <netRelation> elements and possibly other network resources (i.e. net entities) also belonging to individual levels. Each <level> expresses a certain level of detail of the network description, while the permissible values of the corresponding @descriptionLevel attribute are "micro", "meso" and "macro". The interconnectedness between individual levels can be expressed using <elementCollectionOrdered> and <elementCollectionUnordered> elements, nested in individual composition <netElement> elements, which consist of individual <elementPart> elements that refer to respective <netElement> elements of a more detailed <level>. Beyond the principles of the RailTopoModel, raiML 3.2 introduces <netTravelPath> elements, which express the possible paths of passage through (mesoscopic or macroscopic) topology network.

## 15.2.2 Functional Infrastructure Layer

The individual elements of the functional infrastructure layer represent, from a functional point of view, real-world objects that are part of the railway infrastructure network and also various specific characteristics of the railway infrastructure. They contain attributes and other nested elements that describe these objects based on the class they belong to. These functional infrastructure elements can be described by <name> and <designator> elements and refer to the <netElement> elements which they are located on. As for this, railML 3 adopts the RailTopoModel principle of spot, linear and area location and in addition, it also introduces the possibility of network location, in which the relevant net entity refers to a specific <network> and describes properties valid for a larger railway infrastructure network modelled in the railML file.

Some of the functional infrastructure entities are the basis for the subsequent railway interlocking and timetable description. For example, a <route> belongs to the railML interlocking subschema and can refer also to selected functional infrastructure elements covered by the route. Similarly, the <signalIL> element, representing a signal in the interlocking sense, can refer to the <signalIS> element expressing the same signal in the sense of functional infrastructure [3].

### 15.2.3 Current Possibilities of Splitting and Connecting railML Files

Although there are requirements for splitting railML files containing the infrastructure description, for example in the case of large networks that need to be split into smaller ones, currently, there are no clearly defined rules how to do that. Not only the splitting itself, but also the possibilities of subsequent reconnection must be considered when designing mechanisms for splitting railML files. This issue may seem somewhat problematic in the current form of the railML 3.2 format, as there is no universal tool to identify elements contained in different files with each other or to determine a common interface between them. One possibility is to use common values of the @id attribute in the form of universal unique identifiers (UUID) [5] for the elements to be considered the same. However, this approach means increased demands for managing the used UUID values, especially regarding their assignment to individual objects, which can be complicated e.g. if they are contained in different source databases. In such a case, the @id attribute no longer identifies only the abstract element of the railML file, but rather the real-world object represented within the file. It basically fulfills the role of a designator, which is another possible way of identifying objects.

In the current 3.2 version of railML, the <designator> element, can be used as a child element of all functional infrastructure entities and <netElement> elements [3]. It identifies a real-world object by the value of an entry in a certain register, which is expressed by the values of its @register and @entry values. This is the most convenient way to identify real-world objects within a railML file, because we can use this optional element within its parent element to express the object designator in many different registers at the same time. Unlike the child element <name>, which behaves similarly expressing naming of various objects within a particular language, the uniqueness of the entry within the specified register is ensured, which satisfies the conditions for unique identification.

For both approaches of element identification – using UUID or designators – it is necessary that the information is contained or represented in both (all) of these railML files in order to connect them. This fact requires that any changes to common parts of different files have to be implemented at the same time, which may not be easy to ensure in all cases and requires an advanced file versioning system.

Another option for identifying elements from different railML files or finding possible relationships between them is the use of locations expressed using <geometricCoordinate> or <linearCoordinate> elements referring to <geometricPositioningSystem> or <linearPositioningSystem> elements [3]. However, it is a question to what extent objects with the same location within one specific positioning system can be considered identical, especially if we consider the uncertainties that may exist when expressing their coordinates using different methods and systems. This approach requires an advanced specification of the conditions for describing elements with coordinates and the necessity of defining rules to be applied in the event that the coordinates of some elements from different files are evaluated as identical when connecting these files.

## 15.3 Problem Statement

Following the description in the previous section about the current situation, it can be concluded that data integration through registers and UUIDs meet modern requirements of a seamless railway infrastructure data network only to a limited extent. On the one hand, registers can contain just a limited amount of information. Another problem is that working with registries is based on string matching, which implies pre-made naming agreements with partners. The use of UUIDs also implies the existence of life cycle conventions and collision avoidance techniques. Also, when using UUIDs in files, there may be redundant elements used for mapping. Even if the same format is used, there may be a problem of incomplete data. For example, the technical documentation of a railway station may not include data on the neighboring line sections.

This paper puts a new focus on the problem of splitting and connecting railway infrastructure network representations: it suggests to develop common semantic rules for splitting and connecting railway infrastructure networks in order to improve their consistency. For proofing this concept, this case study describes two scenarios: the splitting of railway networks on topology level and the data integration on the basis of functional infrastructure elements.

## 15.4 Splitting of Railway Infrastructure Networks at the Topological Level

Since existing tools being used to connect or split railML files have their limitations, which were mentioned above, the intention of this approach is to extend the railML 3 data format specification in such a way that this can be done more efficiently and, from a technical point of view, highly independent from a specific use case. In this section, we will focus on the possibilities of splitting railML infrastructure files at the topological level. First, the basic assumptions will be defined. Then, an insight into the representation of the topological layer in the form of a graph will be provided, allowing us to apply existing algorithms related to graph search to our problem. Subsequently, we will introduce the issue of series disintegration of network elements, which we can use in the case that the existing description of the topological layer does not conform the assumptions for splitting. Based on that, we will design techniques to indicate where the railML file should be split and to allow the split files to be reconnected. In this regard, two possible options are proposed. These are the “placeholder approach” and the “connector approach”.

### 15.4.1 Preconditions

The main idea of splitting infrastructure networks at the topological level applied to railML files is to split them using selected <netRelation> elements. The design of the splitting methods presented in this paper will respect the principle that each <netElement> contained in one of the newly created files must be covered by net entities to the same extent as the one in the original file. In the following, such a <netElement> will be referred to as a completely described element. The only exception is that the relevant <netElement> would be tagged as incompletely described in a defined way. Another conceivable exception would assume such a way of splitting, where the own aim would be to separate net entities according to their types into different files, while the topological layer would be preserved for all these files. However, this specific case is not being considered in this paper.

Keeping in mind the mentioned assumptions, the starting point is that we must be able to select all the <netElement> elements of the original railML file that are to be included in the newly created file. This applies to all files newly created based on the original one, regardless of how many there are to be. If the intention is to split the original railML® file in such a way that each of the <netElemet> elements appearing in this file is to be included as completely described in just one from those new files that are being created, it is recommended to proceed in such a way that the <netRelation> elements intended to be used for splitting are listed. This list of <netRelations> elements can be both created manually (e.g. by selecting them using a graphical interface of a software able to visualize railML) and be generated on the basis of some defined rule.

### 15.4.2 Graph Representation of the Topological Layer

The topological layer of a railML file within a certain <network> at a certain <level> can be expressed as a graph the vertices of which represent individual <netElement> elements and the edges of which represent individual <netRelation> elements. Suppose that the original file intended for splitting describes the <network> n at the <level> l, in such a way that its topological layer can be expressed using a connected undirected graph T and we have obtained a list of the <netRelation> elements RS of the <network> n and the <level> l which are intended to be disconnected for the purpose of this splitting. By removing the edges that represent the <netRelation> elements listed in the list RS from the graph T, we get a new graph T*. If the graph T* is not a connected graph, the list RS can be used for splitting.

The individual <netElement> elements can be divided into sets based on connected components of the graph T*. Let's assume that the graph T* has connected components. Then, it is possible to divide the <netElement> elements into k disjoint sets. We will denote these sets as D1, D2, … Dk. Each of the Di sets should contain the <netElement> elements that are represented by vertices located in the same component of the graph T*. This can be done using graph search tools, e.g. by traversing the graph using the depth first or breadth first search algorithm adapted to discover connected components [6] [7]. It is possible to use the same algorithm that can be used when integrating <netElement> elements of a certain reference <level> lR into <netElement> elements of a less detailed <level> lG [8]. The individual received Di sets are to be used as a basis for the subsequent creation of split files. The splitting is thus carried out based on the topological decomposition principles. Each of the split files is supposed to contain exactly those <netElement> elements that belong to the corresponding set Di and those <netRelation> elements used to connect these <netElement> elements.

### 15.4.3 Preparing a railML file for splitting

Not in all cases it is a good solution to start splitting a railML file directly. This may be the case, for example, if the dividing of the topological layer structure into <netElement> elements is not appropriate to the desired splitting intent. In that case some <netElement> elements need to be disintegrated. This can be applied primarily to the linear <netElement> elements. The series disintegration of a linear <netElement> means the interruption of this element at one or more defined spots, which is done by the replacement of the original linear <netElement> by new linear <netElement> elements gradually connected by <netRelation> elements, and by the adjustment (or replacement) of all <netRelation> elements by which the original <netElement> is connected to the elements of its surroundings performed in such a way that the value of its @elementA or @elementB attribute is updated appropriately. At the same time, all references to the original <netElement> must be adapted to the new state. This also applies to elements used to locate network entities. For that reason, in some cases, for example, it is also necessary to decompose the <associatedNetElement> elements used by <linearLocation> and <areaLocation> elements.

With regard to how line elements are described (they may or may not have their absolute length expressed in meters, which is represented by the @length attribute, defined), the <spotLocation> and <associatedNetElement> elements can use their attributes to define intrinsic coordinates and possibly also the absolute position in meters to express the location of the located net entity relative to the respective <netElement> [3]. The values of coordinates and positions related to the disintegrated <netElement> must be recalculated. An example of how to recalculate intrinsic coordinates and positions when disintegrating a linear <netElement> using the series disintegration principles is shown in the Figure 15-1.

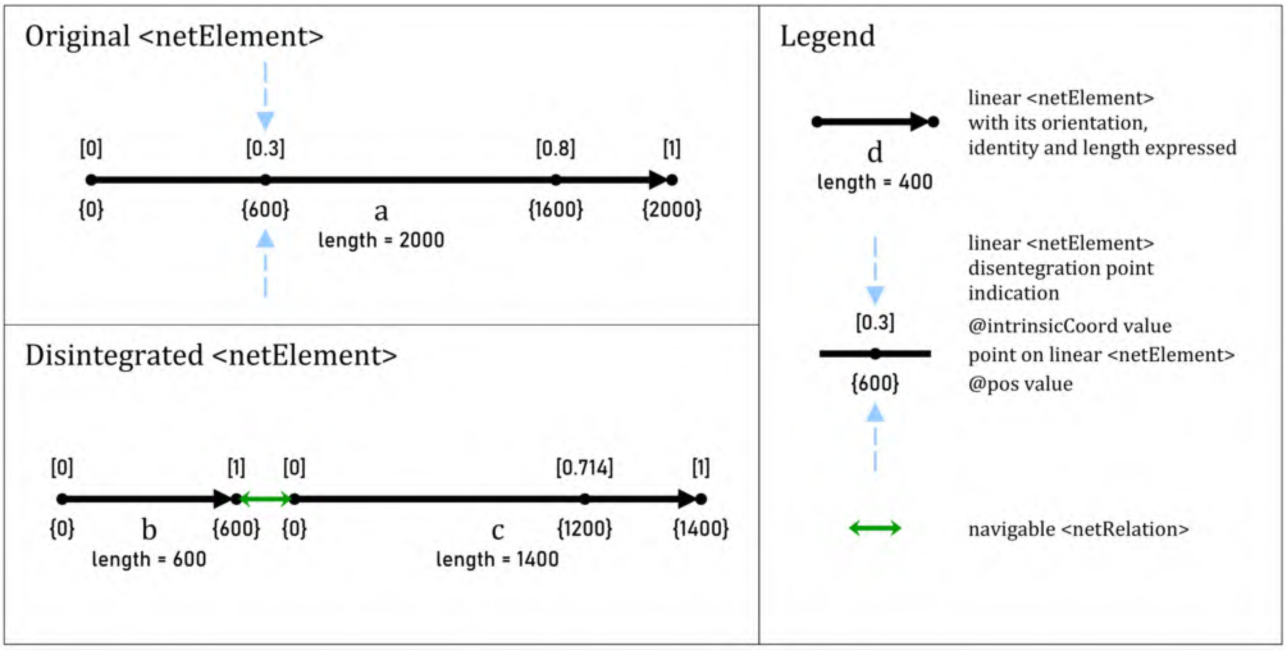


Figure 15-1: Series disintegration of a linear <netElement> with recalculation of positional attribute values

### 15.4.4 Placeholder Approach

For the split files, in many cases it is crucial to indicate where the split was made in order to handle references to elements that do not exist within a given split file and to allow prospective reconnection of these split files. The placeholder approach can be used for this purpose. This approach proposes to introduce a new railML 3 element called a placeholder. The

<placeholder> is supposed to be designed as a minimal element the complex type of which is derived from the {tElementWithID} abstract complex type. Except for @id, its only attribute would be the @placeholderType attribute. The mission of the <placeholder> element in the split railML file is to represent such an element that does not exist in it, but it is necessary to refer to it from some other element that exists in this file. Although from a syntactic point of view it is not necessary for an element to exist within the file from where it is referred to, sometimes its presence may be required due to the modelling principles (e.g. of the RailTopoModel from which railML derives some of its complex types) and in any case it is good to have an overview of these references, even if only with a view to easier reconnection of split files by identifying original elements in one file with the <placeholder> elements of another file and vice versa.

When creating the <placeholder> elements while splitting a railML file, each <placeholder> should get the same @id attribute value as the original element it represents. Applying this to the topological layer splitting based on the list of <netRelation> elements to be disconnected which created two split files, in both of these newly created files, only those affected <netRelation> elements would be duplicated, unchanged, and for each of them, one of the originally connected <netElement> elements would be replaced by a <placeholder> element with the same value of the attribute @id as the original <netElement>. For two linear <netElement> elements connected by a <netRelation>, this is demonstrated in the Figure 15-2. The @placeholderType attribute should express the type of the original element from which the <placeholder> originated. These values could therefore be introduced based on the names of the railML elements that are intended to be replaced by these <placeholder> elements. It implies that placeholders can be used not only to represent absent <netElement> elements, but to represent any element that can be referenced within a railML file, even outside the infrastructure subschema. Therefore, it is recommended not to include the specification of the <placeholder> in the infrastructure subschema, but in the common subschema.

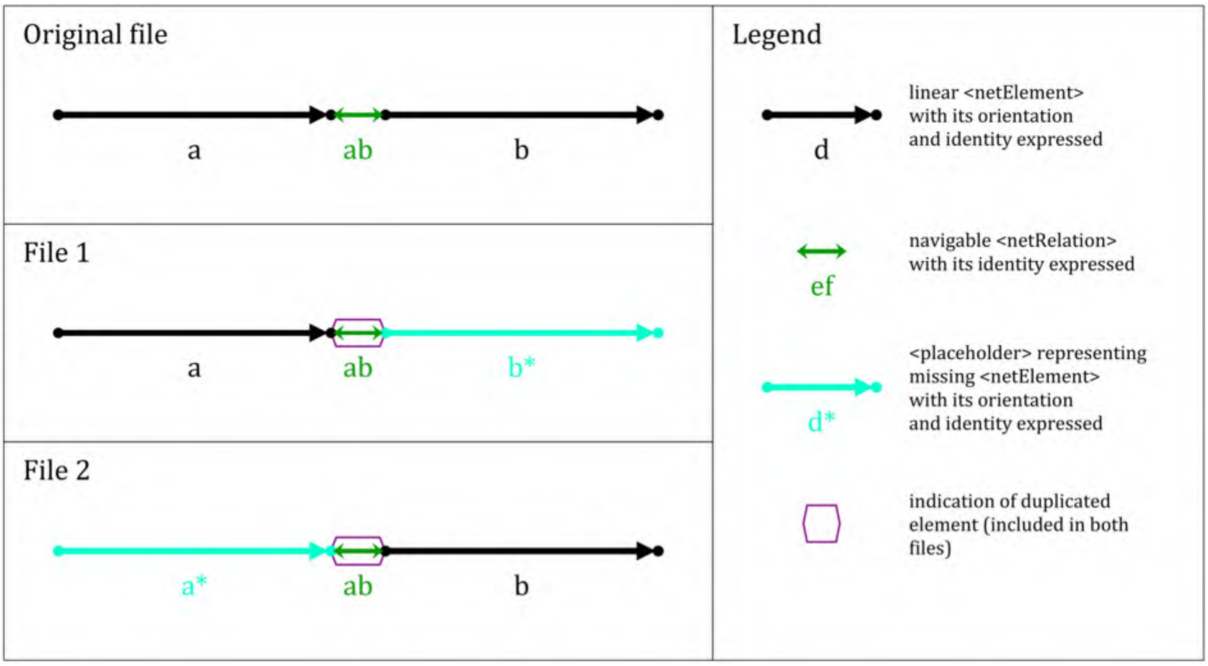


Figure 15-2: Application of the placeholder approach when splitting a file at the topological level

The placeholder concept is quite similar to the solution presented in the railML forum by Thomas Langkamm, suggesting tagging the objects that are not completely described as border objects [9]. In contrast to the pure placeholder approach, this solution would additionally allow some other attributes to be expressed for the elements representing these objects. This would involve introducing a new attribute or nested element for selected types of railML 3 elements such as @isBorderObject or <isBorderObject>. If we use the placeholder term in this sense, we can also name it as @isPlacehoder or <isPlaceholder>. An alternative way to identify sets of non-completely described objects within a railML file would be to reference their core elements from the element representing the collection of them. This could be done, for example, using the <network> elements or perhaps better their <level> child elements. Again, this would most likely require the introduction of a new railML attribute or element performing this function.

## 15.4.5 Connector approach

An alternative to the placeholder approach for splitting railML files at the topological level is the connector approach. It again assumes the introduction of a new railML 3 element, this time called a connector. Unlike the <placeholder>, the <connector> is supposed to be intrinsically connected to the infrastructure scheme, specifically directly to the topological layer. Its complex type is assumed to be derived from the {RTM_PositioningNetElement} complex type, in the same way as the complex type of <netElement>. The main intention is that <connector> behaves in the same way as <netElement>, with the only difference that <connector> can be considered an even more abstract element than the <netElement> itself. The basic purpose of the <connector> would not be to represent a base to which net entities can be anchored but a common interface between two <netElement> elements included in different files. As such, it can be connected to <netElement> elements using <netRelation> elements. A <connector>, like a <netElement>, could be referred from individual <level> elements of the described <network> and their aggregation across different levels of detail could also be done in the same way. In addition, it would be possible to describe the <connector> element with the coordinates of the defined positioning systems.

When creating the <connector> elements while splitting a railML file based on the list of <netRelation> elements to be disconnected, a transformation of the original file can be done first. This transformation assumes replacing each <netRelation> from the list with a <connector> and a pair of the <netRelation> elements that connect this <connector> to the <netElement> elements originally connected by the replaced <netRelation>, such that the newly created <netRelation> elements are connected to these <netElement> elements in the same way as in the case of the original <netRelation>. When the file is subsequently split, the only duplicated elements of the topological layer are the <connector> elements. In the Figure 15-3, this principle is again demonstrated on a simple example of disconnecting the <netRelation> connecting two linear <netElement> elements.

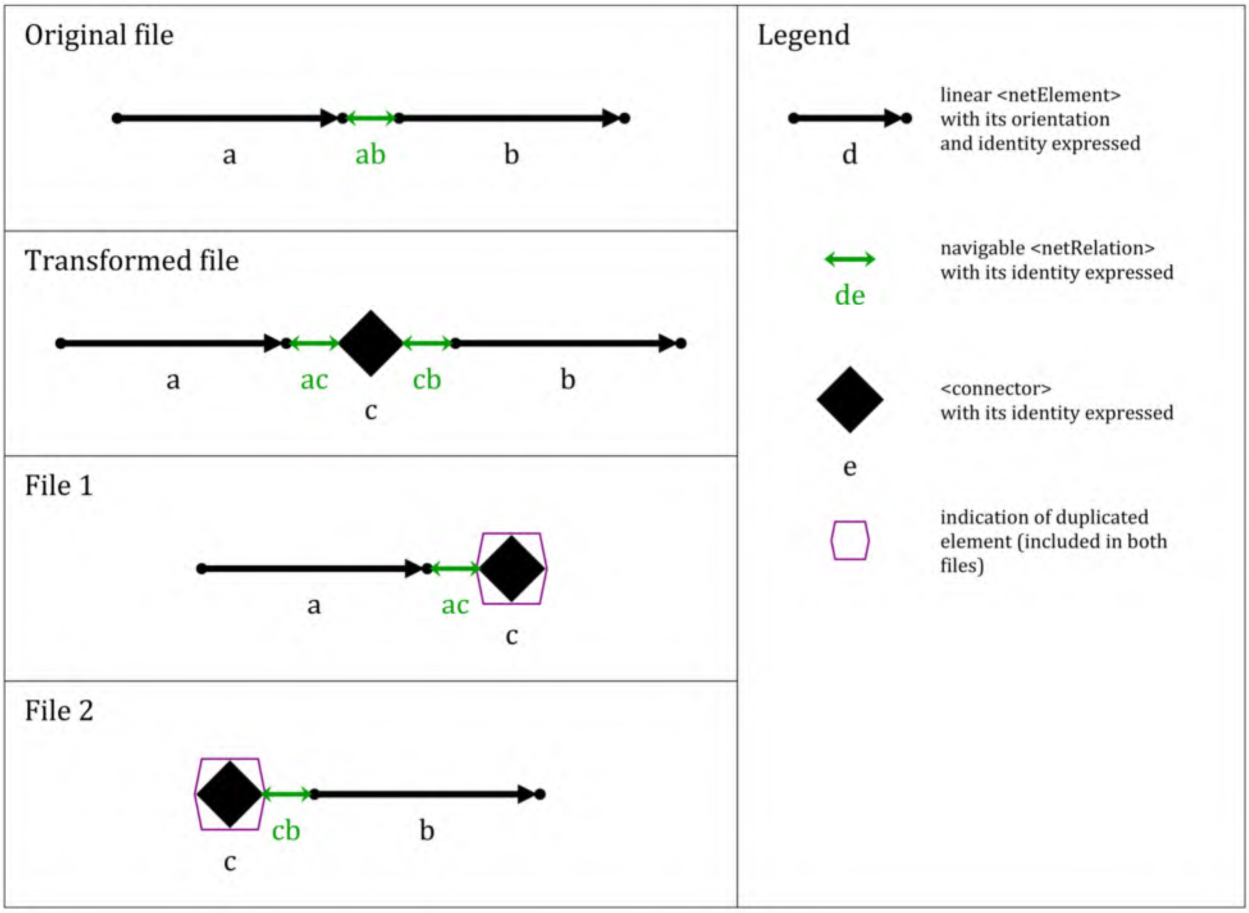


Figure 15-3: Application of the connector approach when splitting a file at the topological level

Since the <connector> that replaced the original <netRelation> intended for disconnection has the same value of the @id attribute in both files into which it was newly incorporated, this can be used later to reconnect the split files. This will make it possible to connect even descriptions of the infrastructure which has been substantially changed. However, <connector> elements can also be built into files that are not originally from the same source to allow them to be connected. In such cases, they only indicate the points of possible connection of the topological layers of different files. When connecting the files, the challenge is then to match the connectors from different files to each other. This can be done based on connecting criteria defined for this purpose. One of these criteria may be the equality of the @id attribute values, if possible expressed in the form of UUID. Another possible connecting criterium is the equality of the coordinates within a specific positioning system assigned to the <connector> elements. It is also possible to use the <designator> elements for these purposes. However, the disadvantage of the <connector> concept is the fact, that it only serves to connect files based on the topological layer, and unlike the <placeholder>, it cannot be used to indicate other interrupted references, which can exist, for example, within the world of functional infrastructure.

### 15.4.6 Further Development of the Proposed Concepts

Two basic approaches to split railML files at the topological level have been proposed, with the intention that the split files could be reconnected. The connector approach is more efficient in terms of applying the topological layer and based on the principles of the RailTopoModel can be applied even outside the scope of railML. In contrast, the placeholder approach can also be applied when managing broken references outside the topological layer, which the connector approach cannot handle. Therefore, the possibility of using a combined approach could be offered, which would benefit from the advantages of both of these approaches.

As for the placeholder approach, it also has several outlined alternatives to choose from. With the connector approach, it is worth considering whether it would be better to understand the <connector> similarly to the non-linear <netElement>, or to the linear <netElement> (albeit with zero length), i.e. if there could be any advantage in distinguishing its orientation. This would definitely be beneficial if more than just two <netElement> elements could be connected to a <connector> by <netRelation> elements.

For both of these options, it is specific that in the case of reconnection, the individual elements must be connected pipe-to-pipe. This can be an advantage in many cases, but there are also situations in which, especially when integrating data from different sources, such an approach is not feasible. Therefore, it is also necessary to consider other ways of data integration, which will be presented in the next section.

## 15.5 Data Integration of Railway Infrastructure Networks at the Functional Level

The problem of data splitting and integration is relevant for example for visualization applications of train routes on a schematic plan of a station. These routes can refer to the infrastructure within the boundaries of one station or several ones. For example, when controlling the movement of trains by dispatchers who are not interested in intermediate stations. However, to ensure data security and consistency, the route must include data of all stations encountered by the train on the way.

While the approaches presented in the previous section involve the extension of railML data model, railway information systems are usually very large and heterogeneous. The administration is reluctant to modernize them and small railway operators may be faced with a lack of funds to change their systems. Another difference is that here, railML 3 files integration is based on functional infrastructure, which makes this approach general enough to be applied to infrastructure files based on other topology foundations as well.

### 15.5.1 Railway Train Routes Aggregation by Ontological Means

The new approach is based on the three methods: railML files interlinking by FAIR data methods, usage of OpenStreetMap as a register and semantic annotation. Data FAIRification workflow includes such steps as reconciliation, ontology development and transformation of existent data into RDF format. These enable data interlinking according to the semantic web principles.

Ontologies are successfully used in different domains so a wide range of ontological tools has been developed. They make it possible not to change the language and data of the existing information systems and have already proven themselves well in transport. In the process of data FAIRification European Railway Agency (ERA) has developed "ERA vocabulary" [10], used among other things to check the compliance of the technical equipment of the rolling stock and the railway track. Other well-known examples are Rail Topology Ontology [11], Rail Core Ontology (RaCoOn) [12], iCity [13], Transport Disruption Ontology [14], MANTO [15] and others. It should be noted, however, that many of these transport ontologies use a limited set of ontological tools.

Linked data methods suggest reusing of existent identifiers, provided by Wikidata, DBpedia and others. For example, they are successfully implemented in The National Center for Biomedical Ontology BioPortal [16]. But publishing of railway linked data is at the initial stage of development, although there are already DCAT-AP, INSPIRE, [17] and SAFETY4RAILS [18] projects.

When integrating data without changing the original information systems, the question of inconsistent naming conventions and entity recognition sharply arises. This problem can be solved by methods of semantic annotation using ontological means. Another way is a fingerprint algorithm clustering that removes punctuation and sorts the tokens alphabetically. This is performed for example in OpenRefine, when preparing data before converting it to RDF. A typical example of messy railway data is the naming of signals in OpenStreetMap and railML® ("Id.L1.UBL" and "Id L1").

When interlinking railML data, the connector element, introduced in the previous section, can be either a new element or an existing one. Here, already existent <description> and <name> elements are used as the connector (Figure 15-4). These elements are sufficient for the railML files to be mapped with Wikidata and OpenStreetMap so performing reconciliation.

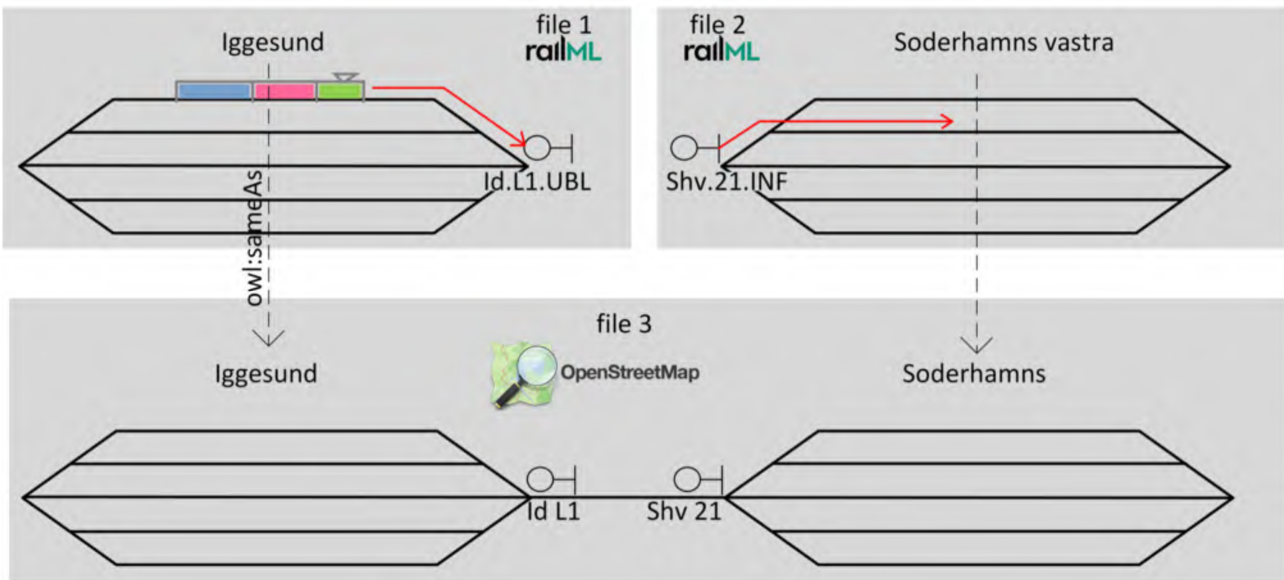


Figure 15-4: railML files integration by ontological means

From a linked data point of view, OpenStreetMap and Wikidata are "connectors". They can be used to link two files, even if the file includes stations located far apart. The advantage of this approach is that the OSM "connector" can be not only a single element, but the whole line section, solving incomplete data problem. In that, railML files with stations are not required to include line sections. This eliminates the "pipe-to-pipe joint" requirement. Missing data can be reused from the open source map.

OpenStreetMap is often used in transport ontology-based applications development (RaCoOn [12] and Transport disruption ontology [14]). Here, Wikidata provides persistent identifiers, so that "reconciliation" is performed as a first step towards FAIR data, i.e. semantic disambiguation. They rule out UUID collision issues and life cycle management. In this case, there is no need for minting UUID or usage of the common register. Mapping is based on extracting knowledge from OpenStreetMap and Wikidata and ontology.

To deal with inconsistent naming of Wikidata, railML data and OpenStreetMap, semantic annotation is used here instead of partial matching. This is justified by the fact that the name of the station "Söderhamns västra" is an official one. In that, a difference between the names "Söderhamns västra" and "Söderhamns station" are not of parsing convenience, but bears semantic information presented in Wikipedia: "The formal name of the operating site is Söderhamns västra to distinguish it from Söderhamn's central station which is now decommissioned (it should not, however, be confused with the old station Söderhamns västra on the state railway Kilafors-Söderhamn-Stugsund, a station which has long since been decommissioned)".

For the transformation of the OpenStreetMap data and enrichment of Wikidata, Chemical Information Ontology (concepts WikidataIdentifier, WikipediaIdentifier) [19], Open Biological and Biomedical Ontologies Relations Ontology [20], friend of a friend (foaf:name) [21], RaCoOn (core:Station) [12], and collections ontology [22] are reused, meaning that these ontologies belong to other projects and domains, but are relevant and applicable for the splitting infrastructure use case.

Let there be three railML data files with one station and part of the route in each file. To perform data integration, one needs to aggregate parts of the route into a new list of routes. The stations must be adjacent because the route must include all the stations of the path. This requires data integration of railML, Wikidata, Wikipedia and OpenStreetMap. Then, one should check railway station adjacency, sort stations according to the order in which the train goes along the line, and connect the complex route to the entry signal of the first element of the list. Data are integrated using OWL tools (owl:hasKey for unique naming conventions, equivalent and functional properties), validation is performed using SHACL, and route aggregation via SWRL rules.

### 15.5.2 Ontological Model of the Aggregated Route

This paper primarily focuses the problem of splitting railway infrastructure description files into parts. It was confirmed that the principles of FAIR data on railway transport allow one to form the requirements to split files and then perform subsequent integration. Although ontologies are used for data integration, the problem of splitting files is equivalent to defining the requirements for file integration. Thus, the question "What should the files to be integrated include?" can be reformulated to "What are the requirements for files to perform data integration?"

The answer is to include a connector element in the file. The advantage of this approach is a disambiguation step towards railML data FAIRification and that elements like <name>, <description> and <designator> are already present in the railML language.

A part of the railML ontology has been developed (Figure 15-5), related to the railway train routes. For data integration, a mapping between the Wikidata ontology and railML was set up, i.e. properties railml3:name, railml3:description, foaf:name, wdt:P296 (station code) are defined as equivalent and inverse functional (owl:hasKey). Railway station adjacency checking is performed using Shapes Constraint Language with the following construct:

```
core:Station a sh:NodeShape ;
    sh:property [
        sh:path wtd:P296 ;
        sh:minCount 1;
        sh:class core:Station .
```

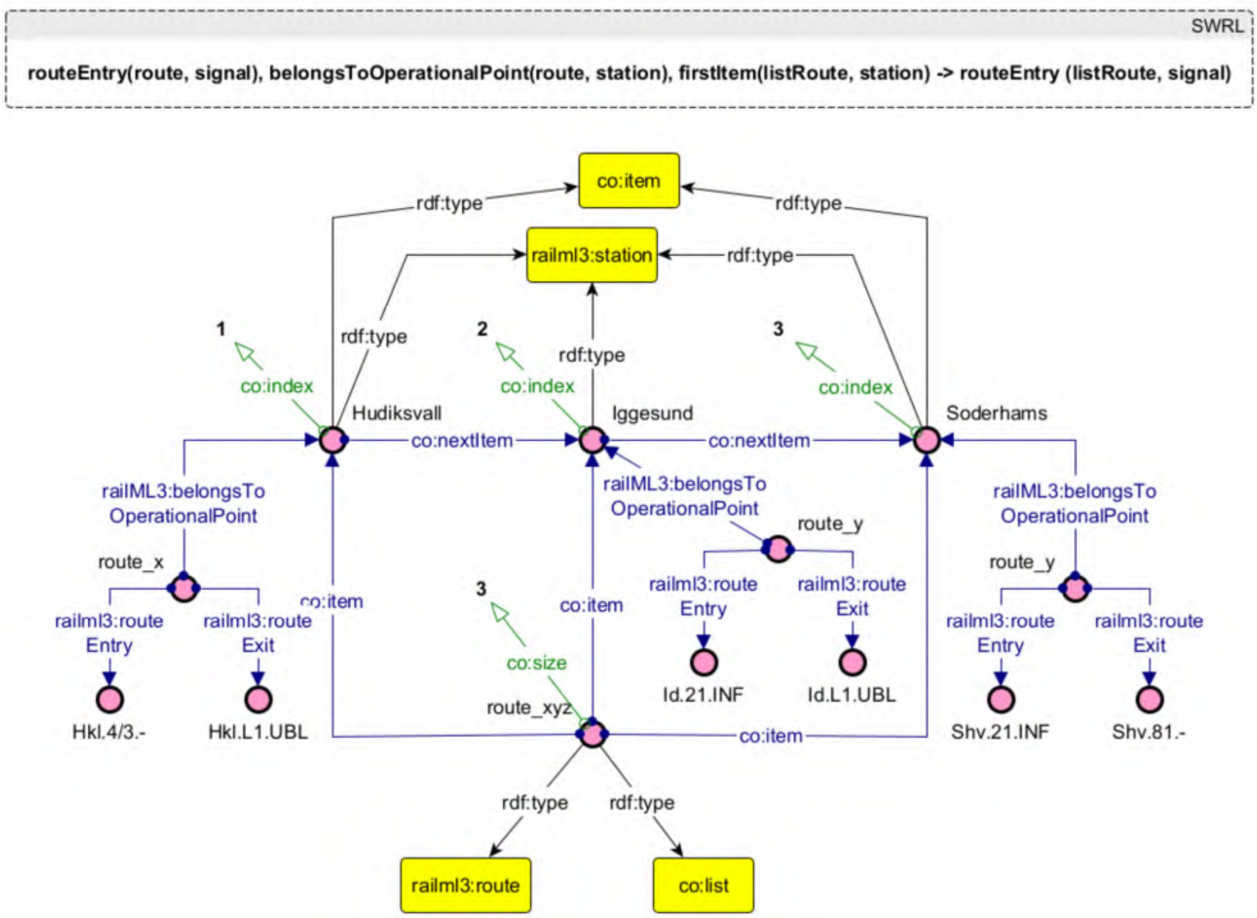


Figure 15-5: Aggregation of routes by ontological means

Figure 15-5 shows the integration of a railML ontology with collection ontology [22] to model route aggregation. In the list of routes, the elements are stations, and the signals are inferred by the SWRL rule: the entry signal of the route of the first station along the route is linked with a complex route.

### 15.5.3 Limitations of the Approach

OpenStreetMap and Wikidata have incomplete data as there are no quality guarantees for these crowd-based open source projects. For example, of the three stations considered in the example (Hudiksvall, Iggesund, Söderhamn) in OpenStreetMap, one did not have a Wikipedia ID, and the other did not have a Wikidata ID. In turn, Wikidata did not have information about the official name of the Söderhamn station.

One of approaches to solving the problem of poor quality OpenStreetMap and Wikidata data is to use more reliable data sources. These may be proprietary maps like GPSInfradat that are created independently of ontology development. In case there is nothing like that creating complete database on scratch may be too time-consuming and difficult to update so one can compensate lack of information by extracting knowledge from the Wikidata ontology or Wikipedia text source using the semantic annotation method. There are also limitations concerning the difficulty to apply this method for the construction use case when moving already existent objects.

### 15.5.4 Further Development of the Method for the railML Data Integration

In the future, it is necessary to consider the direction of the routes, railway switches that are intermediate elements of the route. Since routes are directed, there can be a problem, for example, if a complex aggregated route consists of two routes, where the first one is directed to the west and the second to the east, then this aggregated route should be considered an inconsistent one. The sorting of stations must be done in the direction of the route.

Another question arises when a railML file includes more than one station. In this case, the belonging of a signal to a particular station should be inferred from the topology since the elements like <belongsToParent> are not mandatory for the signals and routes.

## 15.6 Conclusions and Open Issues

In this paper, different methods for splitting and connecting railML infrastructure files for data integration have been developed and presented. The first one utilizes the means of XML schema and RailTopoModel to develop some of the rules for a standardized approach towards splitting infrastructure network representations. The other one suggests not changing existing files and language, but creating a kind of wrapper to perform data integration. Both methods are heterogeneous in that one of them focuses on the topological layer and the second one is based on functional infrastructure elements. Ongoing work investigates strategies for combining these two methods in a complementary way to explore possible synergies. For instance, one possible way is to utilize the fact that both methods contain the concept of "connector" in them, meaning that to split a file one needs to add connectors into them and to integrate files one needs to utilize already created connectors.

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## 15.8 Authors

Dipl.-Ing. **Christian Rahmig** (m) graduated at the University of Technologies in Dresden in the field of Transportation Engineering with focus on Transport Telematics. He joined DLR Institute of Transportation Systems in the year 2009, where he contributed to a lot of national and international projects focusing on multi-sensor data fusion, on-board positioning, digital maps and data models for usage in railway applications. Since 2015, he works as business developer for the Institute, at first for the Railway Department and since 2021 for the Department of Information acquisition and data modelling.

E-Mail: christian.rahmig@dlr.de

MSc. PhD **Larysa Zhuchyi** (f) got a master's degree in "Transport Technologies" at the Dnipro National University of Railway Transport named after Academician V. Lazaryan. She also worked at Dnipro railway yard as station dispatcher and worked for Ukraininan passenger railway department as conductor. Her area of interest is railway knowledge engineering. She will support the further development of railML as ontology researcher in future.

E-Mail: larisa_zhuchiy@ukr.net

Ing. **Adam Hlubuček** (m) graduated at the Czech Technical University in Prague, Faculty of Transport Sciences, in the field of Transport Systems and Technique, where he is currently studying for a Ph.D. in the field of Engineering informatics in transport and communications. Between 2015 and 2020, he worked for the Metrans Rail railway undertaking company as an assistant dispatcher. Since 2020, he has been employed at the Czech Technical University in Prague, Faculty of Transport Sciences, at this time as a researcher. The primary focus of his work is the data description of the railway infrastructure.

E-Mail: hlubuada@fd.cvut.cz

Dipl.-Ing. **Vasco Paul Kolmorgen** (m) graduated at the Technische Universität Dresden in Saxony / Germany in the field of Transportation Engineering with focus on Railway Transport. His main fields of activity in the railway sector are the creation of timetable concepts in a holistic approach of infrastructure and rolling stock data and fulfilment of traffic needs. Here, a particular focus of the activity is on the collection of railway infrastructure data and modelling in planning systems.

At railML.org, he leads the governance of the overall project and the linking of the individual railway schemes.

E-Mail: coordination@railml.org

# 16 Towards Safe and Reliable Autonomous Train Operation: A Digital Map Specification Framework for GoA4

*Nadia Chouchani; IRT RAILENIUM, Famars, France*

## 16.1 Introduction

The development and use of digital maps for autonomous trains is an important and interesting topic that has the potential to revolutionize the way trains operate, improving safety, efficiency, and sustainability. A Digital Map (DM) provides a detailed representation of the physical and virtual environment in which the train operates, including information on the track layout, signaling objects and overall railway infrastructure. The Reference CCS Architecture, an initiative facilitated by the ERTMS Users Group and the EULYNX consortium, defined DM as "a set of functionalities providing track and trackside infrastructure information in the form of structured Map Data, including quality criteria for the data. In addition, it also ensures map management functionalities like map versioning, and download of Map Data" [1]. The latter is provided to consuming systems to ensure specific functionalities such as train localization and environment perception.

This research paper focuses on the DM specification related to the autonomous trains grade of automation 4 [2]. The overall architecture of the autonomous system is defined by X2Rail-4 , a European research project about advanced signaling and automation systems. DM is a crucial building block within this architecture and interfaces with different track-side and on-board sub-systems.

## 16.2 Digital Map overall framework

In this work, we propose a DM system design based on holistic approach, model driven and agile development. In fact, DM is a complex system, and to be effective, efficient, and adaptable, we should take into account the entire system, its environment, and the different involved stakeholders. Figure 16-1 presents the overall DM framework architecture, which is detailed in the following.

The DM has two main missions: first to provide the static map data necessary for the GoA4 operations; and second to manage the objects lifecycle to guarantee that the map data areup to date. These missions reflect the operational vision of the architecture. At this level, DM interfaces with external systems such as:

- "Infrastructure Manager" (IM) which provides the raw input data describing the railway network infrastructure.
- "Operation execution" (OE) sends to REP the Journey Profiles which include the parts of the infrastructure to be mapped to accomplish the train's mission. This system is in possession of dynamic data such as the state of the signals which can be retrieved from the Train Management System (TMS).

- "Repository" (REP) is the on-board sub-system that interfaces with DM to communicate map data.

To accomplish these missions, DM has core functions of input data retrieval and analytics, map data production according to the users needs and the synchronization that guarantees map update. Based on these functions, how DM system should be structured? In our work, we propose four main components. "Input data management" treats the input data to analyze them and put them in a structured format that can be used later. Indeed, the input data can be of different types and in different formats. The processed data feeds a high-level model, which is unique and centralized. It is contained in "Map Provider" component. The conceptual data model is detailed in a next section of the paper. This last component is used by "Digital Map services" which provides services that meet user needs. It provides different views of the centralized model depending on the information presented. Finally, and to manage the map data life cycle and to guarantee that those produced are always up to date, we consider a last component "Sync Service".

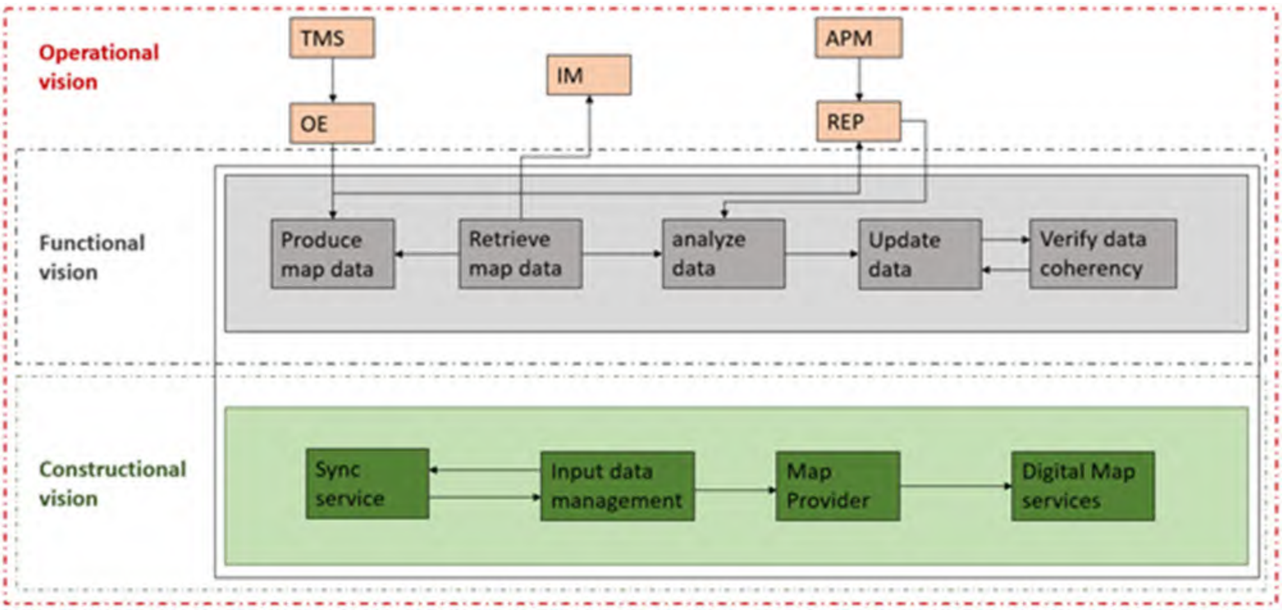


Figure 16-1: Digital Map overall framework architecture

## 16.3 Conceptual modeling

Conceptual data modeling is an important step in the DM design process. In fact, it helps to ensure that the system meets the needs of the users in an efficient and effective manner and can be easily maintained over time.  A conceptual data model is a high-level representation of map data entities, their attributes, and the relationships between them. This abstract representation does not depend on a specific technology or data management system.

The purpose of the DM conceptual data model is to provide a clear and concise representation of the data requirements. It aims to identify the entities and relationships within the map data and provides a foundation for designing the output services. In our work, the conceptualization is not only based on DM requirements for autonomous systems but also meets the international initiatives of standardization. In fact, RailSystemModel (RSM) [3], IFC Rail [4] and Eulynx [5] conceptual models were aligned with the system requirements to produce the DM conceptual data model (DM CDM in Figure 16-2).

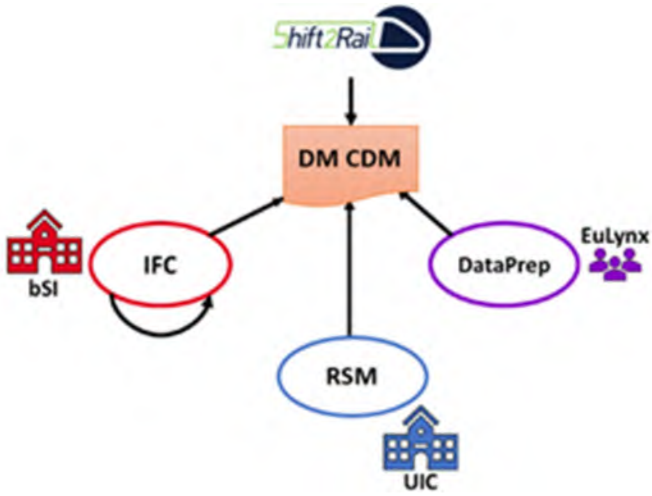


Figure 16-2: Digital Map conceptual data model inputs

In our work, the DM Conceptual Data Model is described by UML package and class diagrams. Map entities are represented as classes, and links between them are defined using relationships. For each class, attributes represent the characteristics of the associated entity. Figure 3 presents an excerpt from this model via a UML class diagram [6]. It describes the tracks topology in compliance with the IFC Rail and RailSystemModel standards.

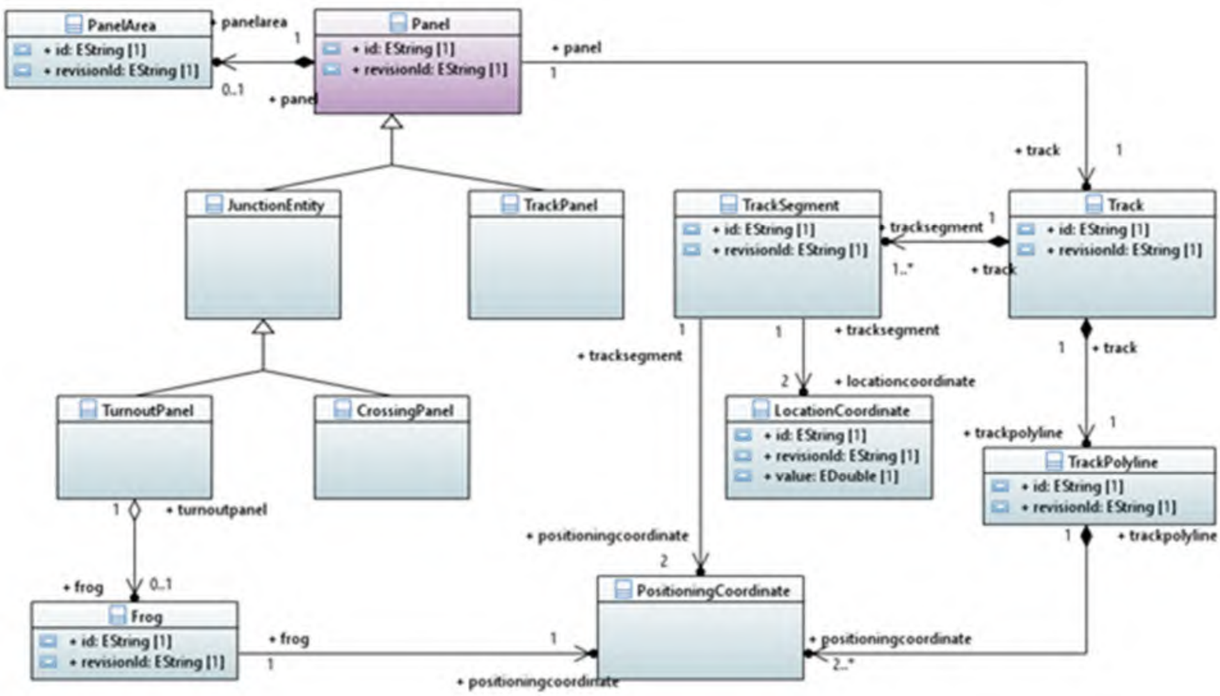


Figure 16-3: Excerpt from Digital Map Conceptual Data Model

## 16.4 Layered architecture

The DM services component is divided into distinct layers, each with a specific view from the conceptual data model and is designed to be used by one or more consuming systems. The layers are independent from one another but are coherent between each other because they are all based on the same centered data model which is available on the Map Provider component. This layered design separates the different concerns of the DM which make it easier to understand, modify and maintain the different services.

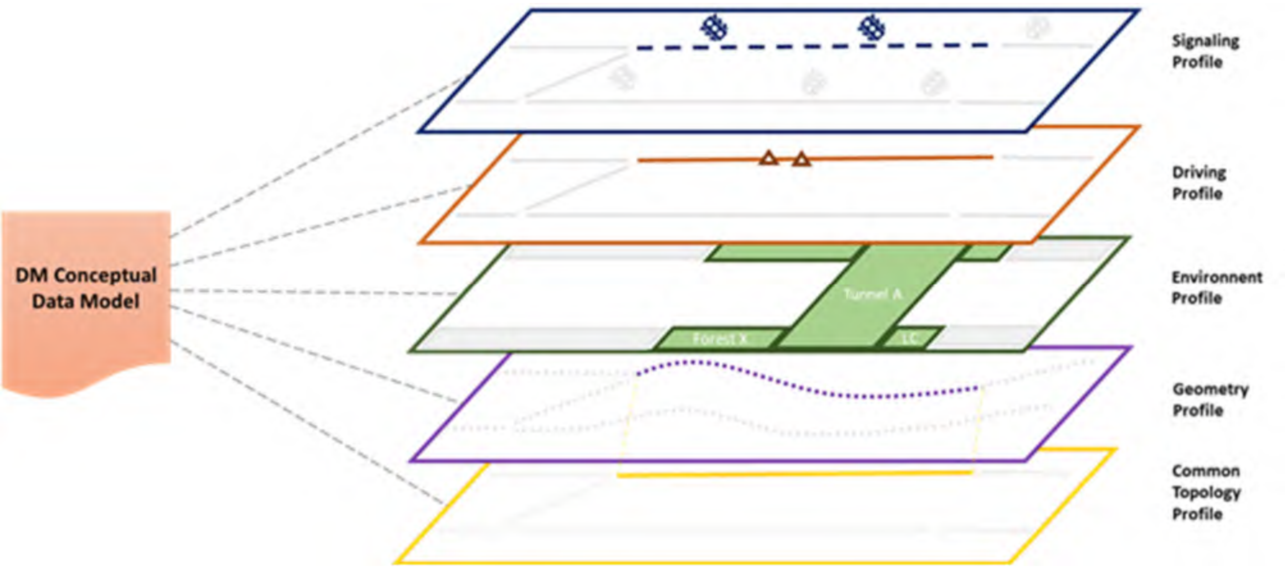


Figure 16-4: Layered Digital Map services architecture

Figure 16-4 details the different proposed layers, which are the following:

- "Common Topology Profile": layer based on the RailSystemModel graph vision, it allows a topological description of train guidance composed of segments of track identified by unique identifiers and positioning coordinates. A positioning reference system is associated to this layer. The segments are the same for all layers.
- "Geometry Profile": this layer describes the track segments geometry layout with sampling in GNSS points used for navigation and positioning. These points are described by 3D georeferenced coordinates.
- "Environment Profile": this layer describes the areas of interest in the environment such as tunnels, level crossings or bridges. These areas are mainly used for environment monitoring and perception systems.
- "Driving Profile": this layer is compliant with a description of the infrastructure in Segment Profiles following the ERTMS SubSet 126 specification.
- "Signaling Profile": this layer provides all the information related to physical and virtual signaling objects for the purpose of detection and interpretation of the related information.

## 16.5 Conclusion

Digital Maps are critical components for the operation of autonomous trains, enabling them to navigate safely and efficiently. The development of accurate and reliable digital maps requires the integration of various methods and technologies, as well as standardization and interoperability across different systems. These maps are created and maintained using various sensors, including lidars, radars and cameras and are continuously updated to reflect changes in the environment. This research paper investigates the design of digital maps for autonomous trains, focusing on the GoA4 grade of automation. We propose a framework architecture which contains a layered design of output map services which presents several advantages. The modularity induced by this architecture allows for more flexibility in the design, development, and deployment of the system, and makes it easier to add or remove functionalities without disrupting the entire system. Scalability is another advantage in the way that additional objects of a layer can be added to handle increased consuming system's needs. Finally, a layered architecture is easier to maintain because it is designed with clear separation of concerns and a modular structure. This makes it easier to fix bugs, add new features, and upgrade the digital map system without disrupting the other layers.

## 16.6 References


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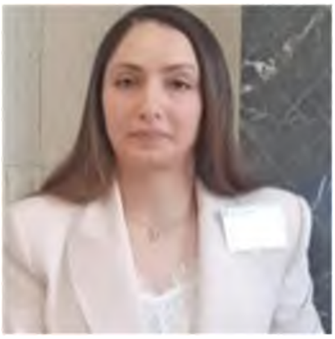
## 16.8 Author



**Nadia Chouchani** is a PhD in computer science from Polytechnic university of Valenciennes, in France. Throughout her academic and professional career, she has focused on Systems Engineering, Semantic and Model-Based approaches; and has published several research articles and papers in well-respected academic journals and conferences. Nadia Chouchani is a dedicated researcher with a passion for Railway domain.

E-Mail: nadia.chouchani@railenium.eu

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