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Towards safer rail control, command and signalling in the context of digitization

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Abstract. Aim. *The state of the art of railway computer-based control, command and signalling (CCS) systems is characterized by high requirements in terms of dependability, functional safety and cybersecurity under the conditions when digital transformation and challenges associated with the demand for increased competitiveness of railway transportation force the transition to new paradigms in engineering, testing, verification, validation and standardisation to facilitate and speed up the process of development and implementation. It is expected that while preserving the level of dependability and safety, at least, as it is, the industry has to enable the maximum possible introduction of innovative solutions and digital tools aimed at further automation of CCS systems to enhance the capacity and throughput of railways and the performance of systems, to minimize the impact of the human factor and reduce the number of failures and downtimes. In this context, the key factors are the interoperability (technical and operational compatibility) of systems and the technological independence of railway operators and infrastructure managers from the designer/supplier of railway automation systems, eliminating the vendor lock-in effect.* **Methods.** *The paper gives an overview of the state of the art of railway computer-based control, command and signalling using the example of the EU and provides an analysis of these systems in terms of dependability and safety in the context of migration to new grades of automation.* **Results.** *The author has considered the evolution of control, command and signalling systems in the EU using the example of the European Railway Traffic Management System (ERTMS). The analysis covered the general trends and approaches to engineering, testing, verification, validation and standardisation of railway CCS systems. The paper has overviewed the major EU research and design programmes of CCS development with the dependability and safety methodology taken into account. A special attention has been given to the methods of open engineering, remote lab testing and standardisation of ERTMS interfaces.* **Conclusions.** *In the context of digital transformation, the development of state-of-the-art railway computer-based CCS systems implies an accelerated introduction of a whole range of innovative solutions and a wide application of commercial off-the-shelf components (COTS), thus making systems more complex and being capable of affecting the dependability parameters. In order to maintain these parameters at a specified level and to minimize the impact of human factors, the railway community is increasingly using formal methods and automated means of engineering, diagnostics and monitoring at all stages of the system's lifecycle. A major factor of dependability is the standardisation of the system's architecture, interfaces, open source design and testing software, including the standardisation of approaches to remote lab testing of products by different manufacturers to prove the reliability of operation at the boundaries of systems of various manufacturers.*

Keywords: *CCS, railway signalling, train separation, dependability, safety, TSI, ERTMS/ETCS, GoA4, human factor, formal methods, verifiction, validation, certification, homologation, testing.*

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1. Introduction

The state of the art of railway computer-based control, command and signalling (CCS) systems is characterized by high requirements in terms of dependability, functional safety and cybersecurity under the conditions when digital transformation and challenges associated with the demand for increased competitiveness of railway transportation force the transition to new paradigms in engineering, testing, verification, validation and standardisation to facilitate and speed up the process of development and implementation. It is expected that while preserving the level of dependability and safety, at least, as it is, the industry has to enable the maximum possible introduction of innovative solutions and digital tools aimed at further automation of CCS systems to enhance the capacity and throughput of railways and the performance of systems, to minimize the impact of the human factor and reduce the number of failures and downtimes. In this context, the key factors are the interoperability (technical and operational compatibility) of systems and the technological independence of railway operators and infrastructure managers from the designer/supplier of railway automation systems, eliminating the vendor lock-in effect.

Strictly speaking, as regards railway CCS, digital transformation implies moving to a new paradigm of control and command of Industry 4.0. In terms of the basic principle of train separation, that means the evolution from simple separation of consecutive trains, first, in time, then in space (by fixed block sections) with further migration to radio-based control and command (such as in the European Railway Traffic Management System, ERTMS) and then to a dynamically changing headway between trains (including train convoys or virtual coupling, i.e. trains running closer than a safe breaking distance, like in road traffic). The transition implies a whole range of normative, regulatory, technological and technical changes [1].

One of the significant factors that underpin the need for a new methodology of engineering and maintenance of railway CCS systems is the increasing automation of train control with targets specified in the European programmes of research and innovation that aim to fully automate train operation, i.e. achieving driverless trains (so called GoA4, or Grade of Automation, according to IEC 62290) [2].

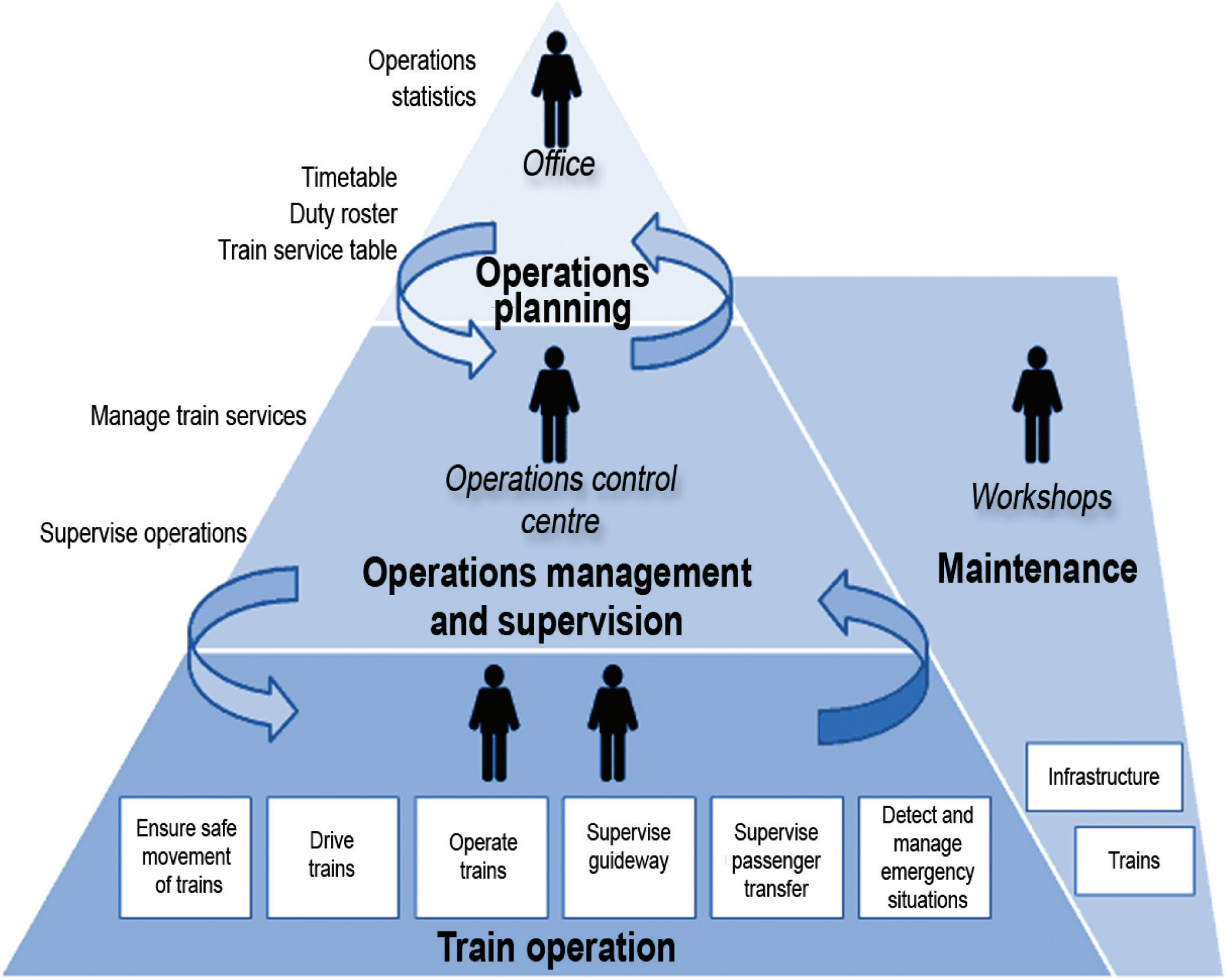

Fig. 1. Organization of railway operations

That emphasizes the importance of dependability and safety issues at all levels of railway operations management, where the human factor now still plays a significant role, especially at the level of safety-related (critical) systems (Fig. 1).

2. EU interoperability and dependability requirements and standards

Historically, practically each nation has its own railway normative requirements and operational rules, and often even a different railway gauge. For instance, before the EU was established, in Europe there were over twenty national CCS systems installed both trackside and onboard trains, as well as individual certification and homologation systems. After the establishment of the EU and opening of the Trans-European transport network corridors (TEN-T), the focus shifted to the issues related to interoperability (technical and operational compatibility) of railway systems and infrastructure and the provision of a common certification and homologation system (so called "cross acceptance system").

Later on, the EU approved the Interoperability Directives and Technical Specifications for Interoperability (TSI) for all components of the railway system including ERTMS that was developed by the European Railway Agency (ERA). In the directives, the interoperability is defined as the ability of a railway system to allow the safe and uninterrupted movement of trains which accomplish the required levels of performance [3].

The current version of TSI relating to Control, Command and Signalling (TSI CCS) is CCS 2016/919 [4]. It specifies the requirements for interoperability of ERTMS trackside and onboard assets, interfaces with external systems, as well as the parameters of reliability, availability, maintainability and safety (RAMS). The interoperability requirements are based on the body of functional requirements specifications for ERTMS subsystems and interfaces developed by the UNISIG group that combines the major European manufacturers of railway signalling equipment, under the aegis of ERA (so called "Subsets").

ERTMS has three core elements:

1. GSM-R (Global System for Mobiles – Railway) is the radio communication element based on the public GSM standard with specific railway frequencies and intended both for a voice communication between drivers and dispatchers and transmission of ETCS data (between the onboard train protection unit EVC – "European Vital Computer" – and the trackside control and command centre RBC – "Radio Block centre").

2. ETCS (European Train Control System) is the signalling system which is responsible for the control of speed, generation and execution of movement authorities, data exchange with interlockings of signals and points at stations.

3. ETML (European Traffic Management Layer) is the level of traffic management based on timetables and intended to optimize train speed profiles at routes using train running data in real time.

ERTMS/ETCS has three variants, or levels. Roughly speaking, Level 1 is the train protection using trackside signals and transponders (balises), with no GSM-R radio communication and, respectively, no RBC in place; Level 2 is the train control using GSM-R radio communication and, respectively, with RBC in place, as well as using balises as reference points along the route for the purpose of navigation (this being the system's variant most widely implemented both in Europe and elsewhere, with a rollout of over 100 ths. km. of railway lines); Level 3 foresees the additional application of onboard navigation and train integrity facilities and the implementation of moving block principle. So far, ERTMS/ETCS Level 3 is more of an experimental system being engineered and tested in the form of some hybrid solutions which integrate the application of satellite navigation, virtual balises and onboard digital route maps.

According to Subset-026 (System Requirements Specification), the ERTMS/ETCS reference architecture looks like as follows (Fig. 2) [5]:

The dash line in the diagram indicates the interfaces that are not yet standardised, and in this case the suppliers' proprietary (closed) protocols and solutions are used. This in particular applies to interfaces between RBC and interlocking installations (IXL) at stations and centralized traffic control (CTC), as well as the communication between radio block centres of different suppliers. This leads to both interoperability and RAMS-related issues.

Besides the list of mandatory functional specifications for subsystems and interfaces of ERTMS/ETCS, TSI CCS also contains a list of mandatory standards whose requirements shall be complied with for the certification of ERTMS/ETCS equipment, i.e.:

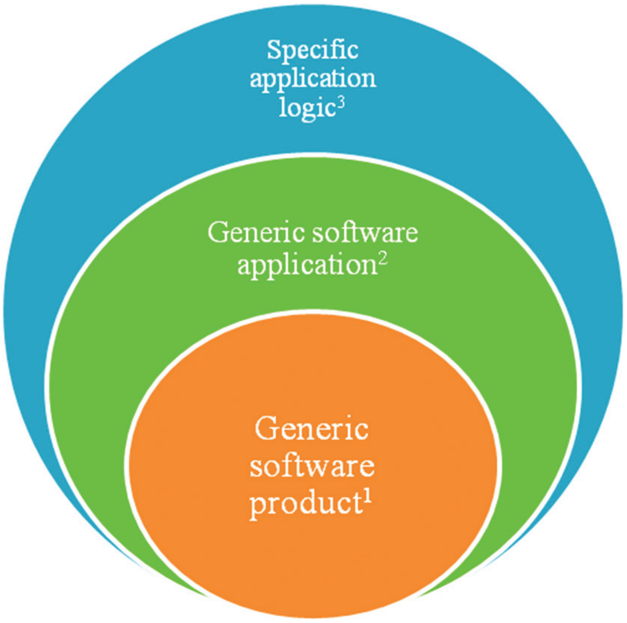
Specific application logic³
Generic software application²
Generic software product¹

Fig. 3. Software layers

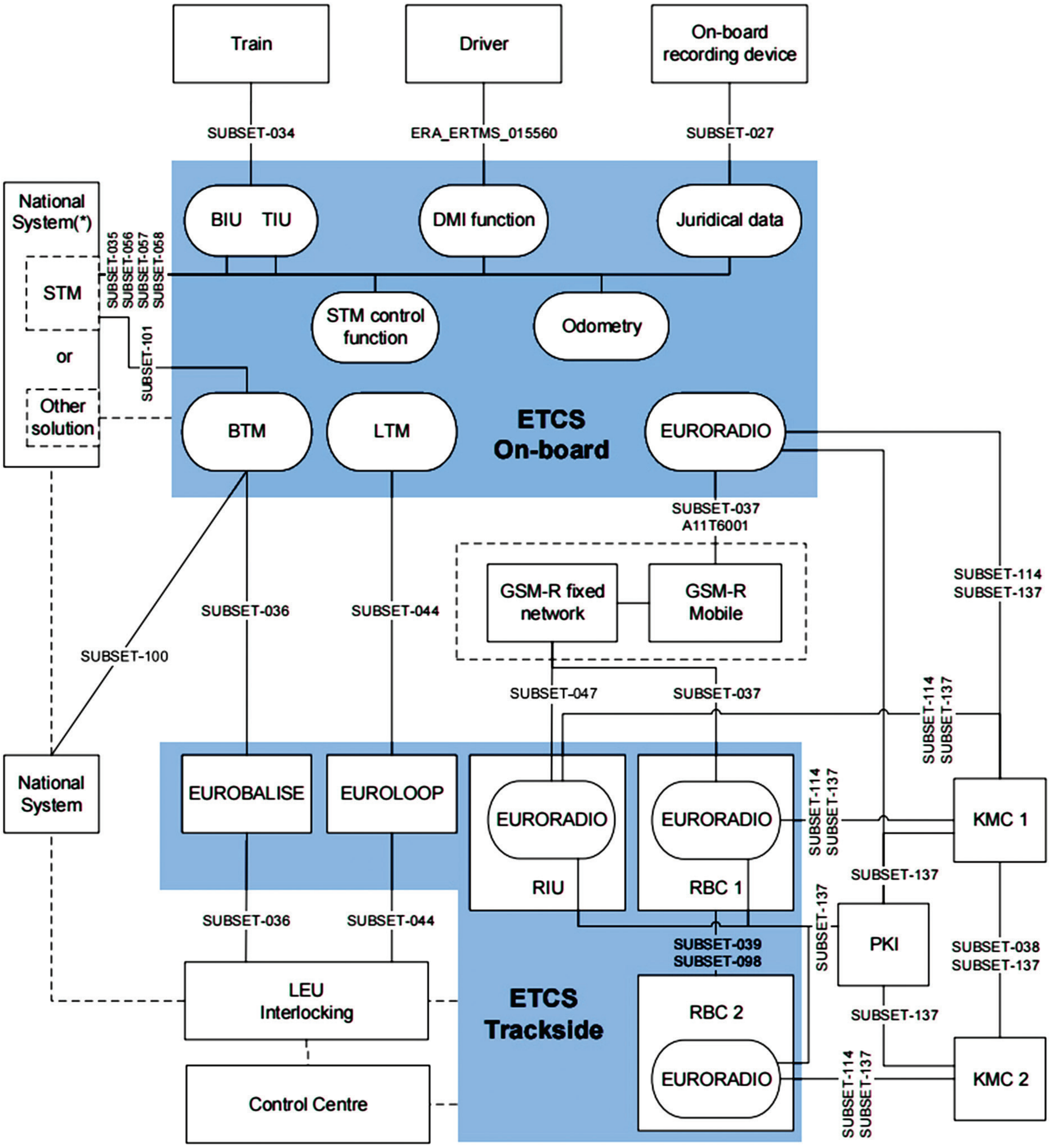

Fig. 2. ERTMS/ETCS reference architecture with functional interfaces specifications

1. EN 50126 Railway applications – The specification and demonstration of reliability, availability, maintainability and safety (RAMS).

2. EN 50128 Railway applications – Communication, signalling and processing systems – Software for railway control and protection systems.

3. EN 50129 Railway applications – Communication, signalling and processing systems – Safety related electronic systems for signalling.

4. EN 50159 Railway applications – Communication, signalling and processing systems.

As to CENELEC, in terms of software, ERTMS/ETCS engineering, verification & validation and certification are to be applied to three layers (Fig. 3):

If we take a look at the key element of ERTMS/ETCS Level 2, the RBC, then we can see that the first layer of RBC is its nucleus that contains a generic safety logic common for all railways where the product is implemented (the product

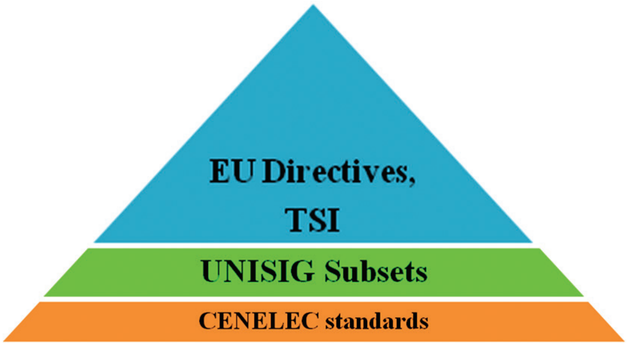

Fig. 4. ERTMS/ETCS regulatory pyramid

is certified once by a European notified body, provided that there are no further changes made to it); the second layer incorporates the signalling logic and rules of the country where the product is intended to be used, and is invariable for all applications of the product at the country's railway lines (requiring homologation for each country); the third layer is a project-specific signalling logic configured for a specific schematic plan and layout (requiring homologation for each project).

To summarize, the regulatory pyramid of ERTMS/ETCS can be presented in a schematic way as follows (Fig. 4):

3. ERTMS/ETCS dependability

The standards describing the RAMS methodology were developed as early as in the 1990s by the European Committee for Electrotechnical Standardisation (Comité Européen de Normalisation Électrotechnique, CENELEC). They apply an integrated approach to the management of RAM parameters directly related to the system dependability and safety (S) of a railway system based on risk assessment considering the lifecycle stages (V-model).

The standards are based on a probabilistic approach and provide quantitative parameters as well as recommendations for ensuring the specified RAMS by using well-proven methods (e.g. methods of programming, automated testing of software, detection and identification of errors and failures). Initially this approach was used in other manufacturing industries such as nuclear power engineering, aviation and space industry, from where it was adopted [6].

The certification of ERTMS/ETCS in compliance with CENELEC standards involves an extensive list of activities related to ensuring dependability and safety (RAMS), i.e. preparation and management of a large volume of documents at all stages of the system lifecycle as well as a strict observance of independence among the designer, the verifier/validator and the assessor of the system and the mandatory production quality management (manufacturing audit).

The RAM documentation includes a RAM programme and a RAM report (internal dependability calculation, check-lists of scheduled and unscheduled maintenance).

To preserve the dependability and operational parameters of the system during its lifetime, one shall define factors affecting RAMS, analyze and evaluate their consequences, use activities related to their control and prescribed by the standards.

According to EN 50126, the RAMS parameters of a railway system are influenced by three sources of failures:

– occurring within the system at any stage of the system lifecycle;

– adverse effects that affect the system in the course of operation;

– errors that affect the system during maintenance activities.

And all these three sources of failures can interact. The efficient management of these factors can keep RAMS as specified. In a schematic way, the relationship of the factors influencing dependability and safety is presented in Fig. 5 [7]:

The performance requirements of a railway CCS system are specific for each system and are thus specified in the agreement between the manufacturer and the infrastructure manager during the design phase. For a system as a whole, there are three defined types of failures:

– immobilizing failure (at least two trains have to be put in on-sight mode);

– service failure (one train at most has to be put in on-sight mode);

– minor failure (which requires unscheduled maintenance, though it doesn't fall under the previous categories).

For example, ERTMS/ETCS RAMS requirements specification (1998) provides the following specific parameters [8]:

– the probability of a train delay due to signalling failures shall not exceed 0.018, while the probability of a train delay due to ERTMS/ETCS failures shall not exceed 0.0027;

– the allowed average delay per train due to ERTMS/ETCS failures, at the end of an average trip of duration of 90 min., shall be not greater than 10 min.;

– the operational availability of ERTMS/ETCS due to all the causes of failure shall be not less than 0.99973;

– immobilizing failures shall not exceed the 10% of the total amount of failures which affect the system's operational availability; service failures shall not exceed 90% of the total amount of failures which affect the system's operational availability;

– the mean time to restore of trackside distributed equipment is 1.737 hours.

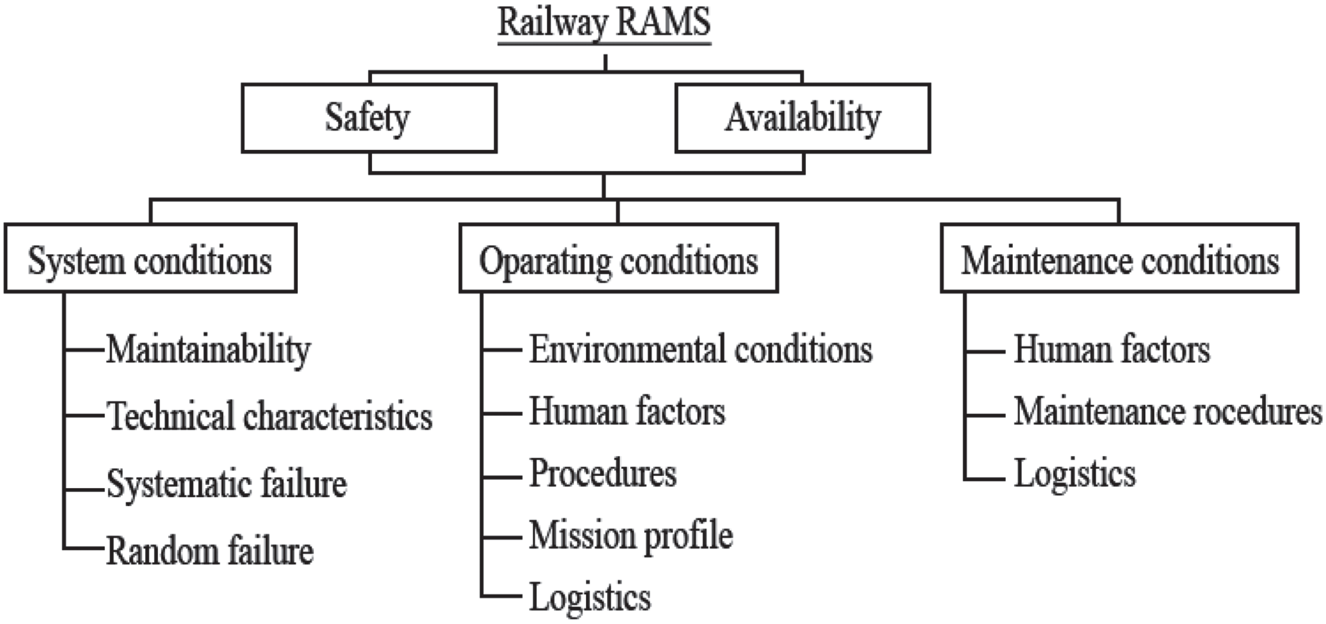

Fig. 5. Factors influencing RAMS (adapted from EN 50126)

However, it is worth noting that ERTMS/ETCS Level 2 is generally an overlay system, i.e. it is installed over a national signalling system and uses it as a kind of fallback in case of failure. There is an ongoing debate in literature about the need of redundancy in the form of external systems to increase the dependability of a primary signalling system [9].

The ERTMS/ETCS RAM programme shall include, as a minimum, the following activities:

– RAM programme planning;
– System conditions and mission profile;
– Periodical RAM programme reviews;
– Reliability modelling, prediction and apportionment;
– FMECA analysis;
– Software reliability analysis;
– Service dependability analysis and verification;
– Preventive maintenance analysis;
– Corrective maintenance analysis;
– Fault isolation and trouble-shooting plans;
– Reliability development/growth testing programme;
– Maintainability preliminary tests;
– Reliability demonstration tests;
– Maintainability demonstration tests;
– Failure data collection from the field (FRACAS).

Naturally, the human factor greatly affects RAMS as well – both at the design stage and in the course of operation. Since humans can considerably affect RAMS, the human factor should be taken into account to a greater extent than in other industries, when achieving the specified RAMS parameters of a railway system. This motivates all the efforts made by the railway community in terms of automation of operation and maintenance as well as of engineering, testing, verification and validation, particularly in the context of a global trend for digitization and the implementation of Industry 4.0 principles.

4. New approaches and requirements

The analysis of the policy papers of the EU railway bodies and associations and those of the International Union of Railways (UIC) shows that one of the key drivers of the search for new approaches and solutions in the railway sector in the context of digital transformation is the low rate of innovations introduction due to a long period of certification and homologation, that is largely driven by the dominance of proprietary solutions in the absence of standardised protocols and interfaces as well as standardised methods of automated engineering. This leads to high costs of development and implementation, operations and maintenance, growing obsolescence of railway systems and vendor lock-in. Also, it potentially impacts their dependability and safety.

In order to find a way out, in 2014 the EU established a joint undertaking Shift2Rail with a total budget of about 900 million Euros [10]. This is an industry-scale innovation programme of railway transportation development that brings together railway manufacturers, operators and infrastructure managers. Its key objectives are the development, integration, demonstration and validation of innovative digital technologies for the railway transport intended to enhance its attractiveness for users.

Shift2Rail is expected to contribute to:

– reducing the lifecycle cost of railway transportation by as much as 50%;

– doubling the current railway capacity;

– increasing the reliability and punctuality of the railway transportation by as much as 50%.

Basically, the changes of approaches to the RAMS specification and demonstration and further on to certification are driven by the business requirements and considerations related to the need to reduce the costs for engineering, certi-

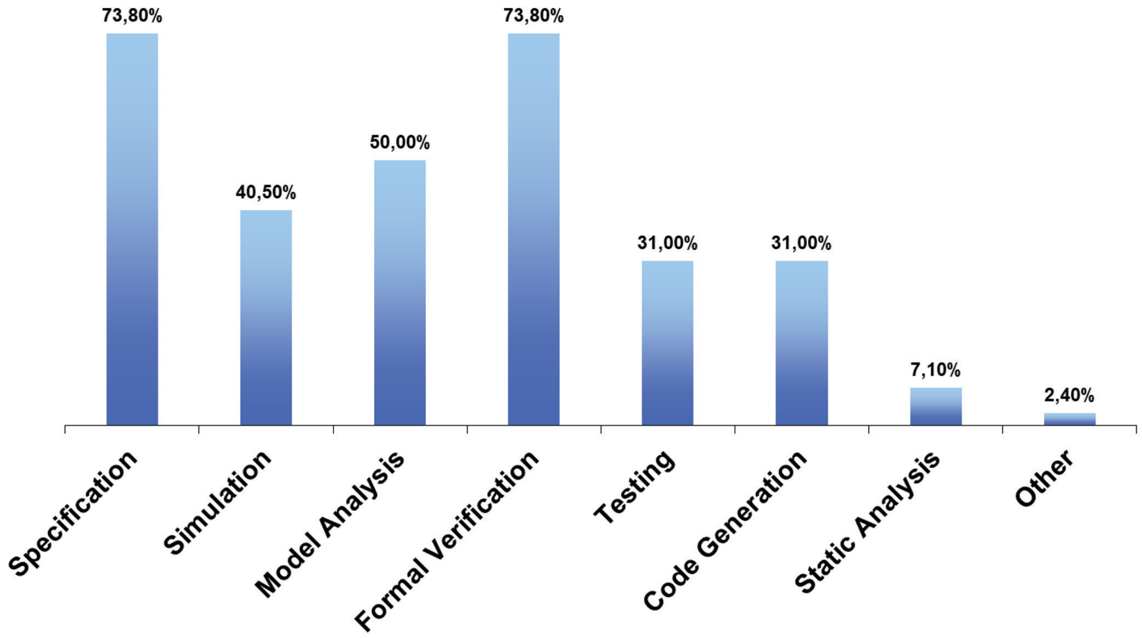

Fig. 6. The application of formal methods at system lifecycle stages

fication and homologation of products and the time to market and on-site installation. Not surprisingly that the Shift2Rail projects research various methods of automation of development, verification and validation, testing processes, including those that are used in other industries – first of all, in aviation and automotive engineering.

Based on selected and then standardised methods, the transition is supposed to be towards virtual certification. By virtual certification one means the maximum allowable use of evidence from virtual testing and simulation based on formal models to support the certification and homologation process [11]. For instance, this methodology is studied

Table 1. The list of the EU projects related to the use of formal methods in railway command, control and signalling

Project	ERTMS/ETCS/CBTC
CRYSTAL	http://www.crystal-artemis.eu/
Deploy	http://www.deploy-project.eu/
DITTO	http://cs.swansea.ac.uk/dittorailway/
EuRailCheck	https://es.fbk.eu/projects/eurailcheck-era-formalization-and-validation-etcs
MBAT	http://www.mbat-artemis.eu/home/69-abstract.html
OpenCOSS	http://www.opencoss-project.eu
OpenETCS	http://openetcs.org/
PERFECT	https://trimis.ec.europa.eu/project/performing-enhanced-rail-formal-engineering-constraints-traceability
	Distributed railway signalling
SafeCap	http://gow.epsrc.ac.uk/NGBOViewGrant.aspx?GrantRef=EP/I010807/1
	Interlocking
ADVANCE	http://www.advance-ict.eu/
EULYNX	https://eulynx.eu/
EuroInterlocking	http://test.swissrequirementsengineering.ch/en/projects/euro-interlocking-project
INESS	http://www.iness.eu
RobustRail	http://www.robustrails.man.dtu.dk

within the framework of the Shift2Rail project – PLASA 2. The objective is to substantially reduce the time required for provision of interface with the existing systems in place and the field testing by standardising interfaces and using formal methods for engineering, verification and remote lab testing.

In fact, it is worth noting that EN 50128 highly recommends the use of semiformal and formal methods for development and automated tools of testing, verification and validation, however there is still much to be done in terms of selection and standardisation of respective methods and tools [12].

According to [13], the approach to ensuring the "development quality" of software presented by the CENELEC standard alone cannot guarantee the correct operation of a computer-based system. It is to increase the "development quality" and to reduce the lifecycle cost of safety-critical computer-based systems, interlocking systems in the first place, why formal methods were introduced. The basic advantage of the methods is that they enable an exhaustive analysis of all possible scenarios of the programmed system behavior while ensuring the consistency between the formalized and proven behavior of the model and the behavior of the code embedded into the system.

5. History and further application of formal methods

The history of the use of formal methods in standardisation of railway signalling started in 1997 when the UIC published the European Railway Research Institute (ERRI) project report that presented a detailed analysis of functional conditions of interlocking systems and proposed the harmonization of functional requirements for signalling systems based on formal methods. Later on, a UIC working group developed a semiformal method called EURIS (European Railway Interlocking Specification), which defined building blocks (e.g. signal, track, point) and described the operations related to each building block using flowcharts. The UIC project EURO-INTERLOCKING (1998-2008) formalized the requirements for an interlocking system that were converted into a formal model visualized by a computer. It appeared that both the skills of a signal engineer and a modelling specialist were needed to do this work. Additionally, it became apparent that that is an iterative process requiring further quality improvements both in the verbal language representation and the requirements coverage [14].

This work was continued within the framework of the EULYNX project where using the SysML models the focus was on the formalized description of interfaces of trackside signalling systems of different supplies, including ERTMS/ETCS subsystems, to reduce the time of their development and software/hardware adaptation. As an extension of these approaches, the ERTMS Users Group and the EULYNX consortium then initiated the Reference CCS Architecture (RCA) project aimed at developing a new ETCS reference architecture integrating ATO functionality (and further migration to GoA4), harmonization of components and standardisation of interfaces and communication protocols based on the use of formal methods. In 2019, an alpha release of a future reference architecture was issued [15].

In parallel with RCA, the initiative of the railway infrastructure managers from the major European countries (Germany, France, Switzerland, the Netherlands, etc.) gave birth to the Open CCS Onboard Reference Architecture (OCORA) consortium with the objective to develop and standardise a next-generation open modular ETCS onboard architecture platform. The OCORA initiative plans to use the EULYNX and RCA approaches and is also focused on the requirements of an updated CCS TSI version to be released in 2022. OCORA strives to negate the vendor lock-in effect (by modularity, interoperability, replaceability, modifiability, security and usability) through the development of a new open CCS communications bus and standardisation of communications protocols of all onboard modules using accepted industry standards as much as possible. It is assumed that such approach will also allow achieving the tangible enhancement of the system performance, as a summary of reliability, availability, maintainability and safety, plus cyber security. According to the project master document, the OCORA deliverables are expected to be a comprehensive and coherent set of specifications as well as new supporting recommendations for integration, verification and validation of CCS onboard implementations with the maximum use of automated testing tools and formal methods [16].

Within the framework of the Shift2Rail-backed ASTRail project, the researchers from the Formal Methods and Tools (FMT) laboratory, which is part of the Institute of Information Science and Technologies (ISTI), one of the institutes of the Italian National Research Council, made an analysis and assessment of major languages and tools for formal simulation and verification used in the railway domain. For example, the research identified [17] that the following automated engineering tools most frequently appear in literature: Simulink, NuSMV, Atelier B, Prover, ProB, SCADE, IBM Rational Software Architect, Polyspace, S3.

The surveys made within the framework of the project revealed that developers use the above or other automated tools for the following purposes (Fig. 6):

The results of the survey showed that formal methods are typically used at the stages of the system specification and verification. The standardisation of approaches to the composition of functional and system requirements specifications (FRS, SRS) as well as to verification based on formal methods is covered by a number of the EU projects, let alone the Shift2Rail programme itself. Thus, starting from 1998 till now, 14 projects have addressed the use of formal

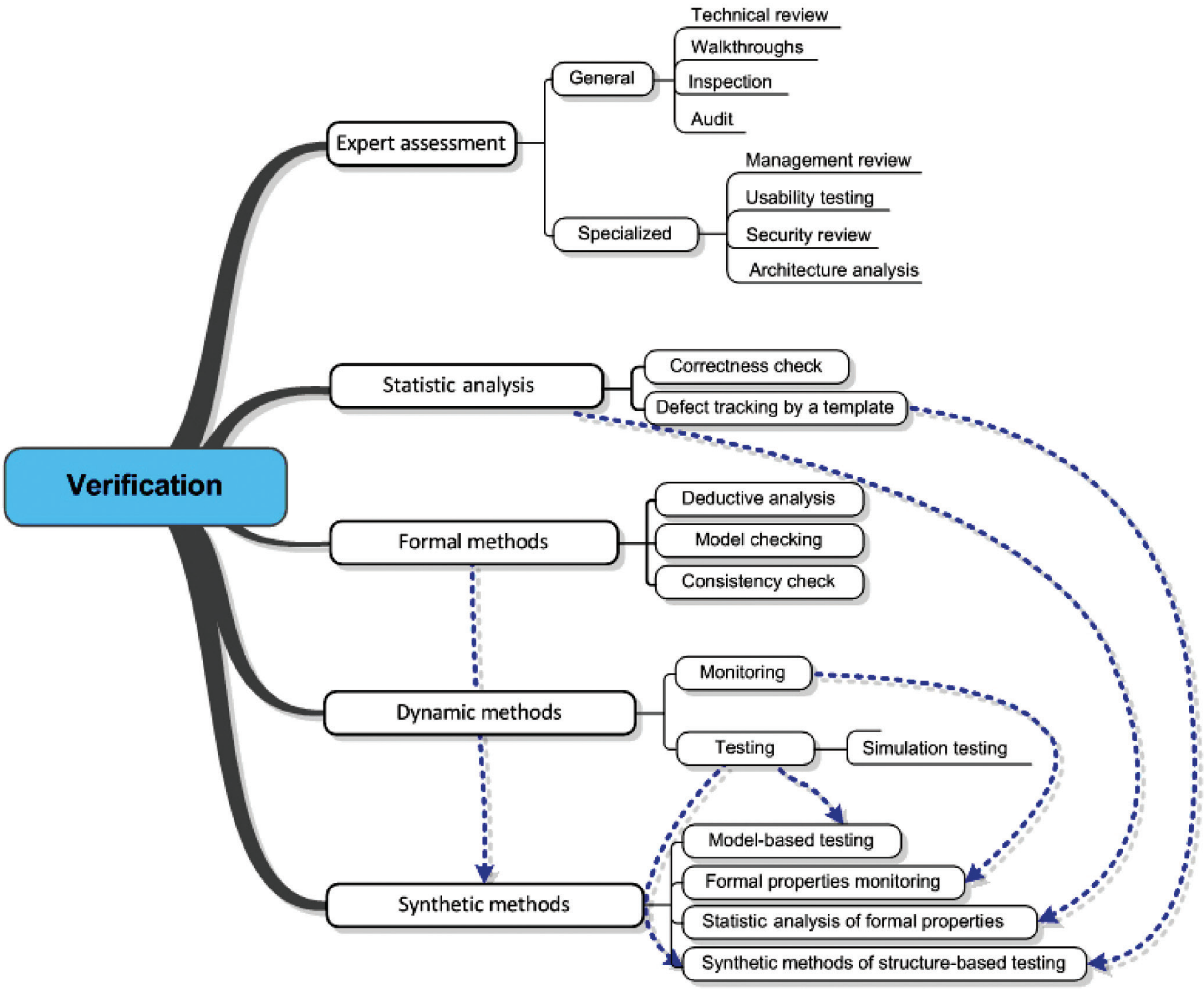

Fig. 7. Combined application of verification methods

methods in railway applications. A detailed description of them is obviously out of scope of the paper, so let us just list them (Table 1):

A detailed analysis of the conventional and formal methods of verification is given in [18]. Generally, the verification process of a safety-related system such as ERTMS/ETCS is made of a set of complementary methods and tools, that at present frequently takes into account not only RAMS parameters but also cyber security (one more area subject to further standardisation in the railway domain, Fig. 7):

A detailed analysis of the capabilities of discrete event simulation as applied to the lifecycle stages of ERTMS/ETCS, in particular to the verification phase, is given in [19]. The author notes that the ERTMS/ETCS system can be characterized by the fact that the system states are discrete, and the transition mechanism of states is driven by events. For safety-critical systems, current engineering methods cannot guarantee that the developed system will respect all its requirements and behave safely, and that shows an urgent demand to integrate verification processes into the system engineering as early as possible. This can be done by using formal languages and formal methods of engineering.

There is a long list of formal methods, but they share certain advantages:

– formal representations have precise semantics that is free from ambiguity;

– formal models can be mathematically verified and thus proven to be correct;

– formal models can be read by computers, and so enabling the automation of the engineering process.

Ideally, the application of formal methods allows avoiding the unsafe transitions of the system states as well as minimizing the number of errors introduced into the system by a designer, and therefore, the number of system failures, which directly affects its dependability.

One of the key sections of the European Shift2Rail railway initiative is its innovation programme IP2, whose objectives include the development of automated tools for simulation and lab testing (remote as well) to reduce the need of integration and validation tests on site (so called “Zero on-site testing”).

In the opinion of the Shift2Rail authors [20], today, as regards the testing of CCS system, the situation can be characterized as follows:

– In most cases, suppliers do product testing in the lab.

– System testing is still done with a large amount of on-site testing.

– On-site testing is often used as a fallback, if lab testing has not been finished in time.

– Lab testing is done mainly by a supplier-specific process and testing environment.

– Collaboration with different suppliers always causes the need for sophisticated adaptors with less chance to reuse them in subsequent projects while increasing costs.

– The test case derivation is not comparable since different approaches have been applied, which are proprietary.

Eventually, in terms of the targeted goals of the Shift2Rail programme and its research and innovation projects, the approaches at all the stages of the ERTMS/ETCS lifecycle are expected to be standardised taking into account the necessity of implementing innovative ideas such as moving block, virtual coupling, perception capabilities as part of GoA4, future railway mobile radio communication standard FRMCS that is under development by the UIC and will be based on IP to replace the obsolete GSM-R standard. The results of the projects are supposed to be the basis for new requirements of interoperability of the updated version of CCS TSI to be released in 2022, as well as, presumably, recommendations for changes to be made to the CENELEC standards.

5. Conclusions

In the context of digital transformation, the development of state-of-the-art railway computer-based CCS systems implies an accelerated introduction of a whole range of innovative solutions and a wide application of commercial off-the-shelf components (COTS), thus making systems more complex and being capable of affecting the dependability parameters. In order to maintain these parameters at a specified level and to minimize the impact of human factors, the railway community is increasingly using formal methods and automated means of engineering, diagnostics and monitoring at all stages of a system’s lifecycle.

A major factor of dependability is the standardisation of the system’s architecture, interfaces, open source design and testing software, including the standardisation of approaches to remote lab testing of products by different manufacturers to prove the reliability of operation at the boundaries of systems of various manufacturers. A potential future development of a common CCS ontology and standardisation of methods and tools for engineering, testing and maintenance based on the principles of interoperability and whitebox solutions to avoid vendor lock-in for railway companies can provide railway transportation with a competitive edge compared to other modes of transportation.

Evidently, there is yet another large area of research and practical activities which has by no means been covered in this paper, and that is the application of digital sensors and digital models, as well as integrated information systems intended for monitoring and prediction of the system dependability parameters, identification of pre-failure states based on the formal description and simulation of possible degradation scenarios using Data Science and Big Data. But this might be a topic for a separate study.

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The author's contribution

Ozerov A.V. has analyzed the key parameters of railway control, command and signalling using the example of ERTMS/ETCS and considering RAMS requirements based on international standards, and outlined the major directions of evolution of the approaches to engineering, certification and homologation withing the framework of digital transformation and transition to new paradigms of innovations implementation.