TRANSPORT PROBLEMS 2023 Volume 18 Issue 3
PROBLEMY TRANSPORTU DOI:10.20858/tp.2023.18.3.01

Keywords: rail transport; model verification; railway infrastructure modeling; multigraph IS; ETCS application

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MULTIGRAPH IS: Part 2. VERIFICATION OF THE DIGITAL TWIN OF THE EUROPEAN TRAIN CONTROL SYSTEM APPLICATION

Summary. The final model for rail transportation is the introduction of full digitalization to support communication and transport services, which will be available to the public in the future. The process of digitalization is based on models that reproduce the real physical structures present in the transport network. Due to the high complexity of the structure and its mapping, it is necessary to find methods that automatically verify the proposed created model. This approach supports manual activities that, at this moment, are not sufficient. Automatization's description requires a formal approach. Such a description has been developed as part of a research project, "The Digital Railway. The digital twin of the ETCS application. Virtual prototyping and simulation of operational scenarios." In this paper, a formal model of the ETCS application has been proposed, and a formal approach to its verification is described.

1. INTRODUCTION

The European Rail Traffic Management System (ERTMS) is a modern solution supported by the European Union to enable the unification of the rail traffic management and railway command control system in Europe. This solution aims to ensure the interoperability of rail transport. The ERTMS system consists of:

- ERTMS/ETCS - European Train Control System (further: ETCS) Command Control System (CCS),
- ERTMS/GSM-R - a digital railway radio communication system based on the GSM standard (further: GSM-R).

The ERTMS is being implemented in all European Union countries as well as outside it (e.g., in Middle Eastern countries). In Poland, it will be installed on railway lines, with a total length of over 7,000 km, and the Rail Baltica project, which will be built with a total length of over 1,740 km (Lithuania – 784 km, Latvia – 530 km, Estonia – 426 km).

The ETCS application is an implemented ETCS system in a specific area of the railway network (e.g., a section of a railway line) and on vehicles that move in it. It creates a complex system (i.e., one built from separable parts: devices and subsystems). In such systems, the difficulties in meeting the indicated requirement do not result from technical solutions that are already sufficient. The barrier is often the substantial amount of knowledge and intellectual effort needed to design the application.

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Currently, in practice, there are many problems when implementing the ETCS system on subsequent lines in the form of:

- the inappropriate arrangement of system components, leading to incorrect implementation of key functions,
- a lack of compatibility between different components of the system resulting in disruptions in train traffic, and
- high costs of preparing system designs and going beyond the schedule of implementation periods.

These problems require implementing new technologies for designing and verifying ETCS applications.

The Railway Traffic Control team of the Faculty of Transport at the Warsaw University of Technology has been implementing the project "Digital Railway. Digital twin of ETCS application - Virtual prototyping and simulation of operational scenarios" [1][2]. Its assumptions include the development of a research framework enabling the progress of new technologies in the designing area and the validation of the ERTMS/ETCS system. In the project framework, a virtual prototype is being developed for the Digital Twin of the ETCS Applications (CBAE). The goal of the new solution is to be able to verify the design of the ETCS application in real-time design activities by means of defined correctness criteria. The verification process is based on criteria defined in a formalized form using the Multigraph IS structure. The criteria are defined in a formalized form by the designer on the basis of his/her knowledge, regulations, and the requirements of the project commissioner. In the following sections of the article, a formalism for modeling an ETCS application based on the Multigraph IS [3] is described. An example of such an application model for a simple track layout is presented. Then, the approach of the formal verification of the application is presented. Finally, examples of formal descriptions of conditions for verification of the correctness of the design of a real system are given.

2. RELATED WORKS

The Multigraph IS concept used was described in a previous article published by both authors [3]. The Multigraph IS is a formalized digital model of the railway infrastructure. Its vertices model the types of railway infrastructure elements, and the edges model the relationships between them. The definition also includes a metamodel containing predefined relationship types, functions, and attributes.

The current practical approach to verifying ETCS applications is a type of dynamic testing under anticipated conditions of exploitation. However, a number of ongoing studies show that the verification of digital railway infrastructure models allows the study of their various properties and brings tangible benefits for the positive completion of a railway investment. Later, some interesting approaches of this type are presented.

A treatment of the problem similar to the Multigraph IS is addressed by [4]. This paper presents EVEREST, a tool for automating the verification of railway network models that maintains the loosely coupled nature of the design process. To achieve this goal, EVEREST first combines two different views of the railway network model – the topology provided in signaling diagrams and plans containing the functional infrastructure and the exact coordinates of the elements provided in engineering drawings (CAD) – into a unified model stored in the standard railML format.

Authors of [5] use ontologies to describe railway infrastructure in various ways. They present a semantic control of the compliance for railway information system data with regulatory documents in terms of the track passport. This is implemented based on a multi-level model of ontology concretization and integration.

Other authors [6] describe the RailCOMPLETE® tool, which, along with an integrated CAD tool, allows the verification of railway designs. They use a variation of the Datalog language and use the standardized railway markup language railML [7] as the base and exchange format for formalization. Verification is carried out in real time ~~out on the fly~~ while design work is being carried out.

The following article [8] presents a concept for a laboratory environment built on a Neo4j database and an application that allows data acquisition and modification of the rail infrastructure model. This allows the simulation of multiple variants of the designed model and its evaluation using the proposed measurement indicators.

The article [9] presents various methods of formal verification of a model of an interlocking system described by using diagrams and enabling automatic code generation. A method is presented to support the extraction of formal properties from older systems designed as relay circuits.

A paper [10] presents a method for optimizing railway line data and verifying the construction process. A formal model of the construction process is established by a model verification method combining Unified Modeling Language with a NuSMV model that verifies its activity, confidence, and transfer of important attributes in the model. The data model and construction process are improved by counter-example analysis to meet the requirements of the signaling system.

The dissertation [11] investigates what sources of error arise from BIM modeling. This is then used to systematically develop automata to support model checking in the field of railway structural design. On the one hand, this facilitates systematic model verification. On the other hand, it helps keep the very large amount of data associated with the models in check.

3. GENERAL ASSUMPTIONS

The functional requirements of the CBAE infrastructure highlight the importance of accurately reproducing the existing railway network with all elements of its infrastructure. When selecting a mathematical formalism for modeling the described solutions, the need to represent the large variety of system elements and the relationships that exist between them are considered. In addition, the mathematical model should be of an open nature to allow the free extension of its structures to include the representation of actual elements that will appear in the future. At the current stage of concept development, the mathematical model describes the topology, geometry, and functional infrastructure to a certain extent.

The main task posed to virtual prototyping algorithms is to verify the correct configuration of trackside infrastructure and ETCS applications. This activity largely consists of searching for relevant elements and examining the relationships between them. Due to the practical nature of the CBAE concept, the selected mathematical model should be characterized by ease of implementation in the form of computer data structures. These structures should allow a high-speed analysis of model properties, extensibility with new elements, and the economical use of operating memory.

It should be noted that the configuration of the track infrastructure is static, so it is worth building a complex data structure that allows the creation of simpler and faster algorithms operating on it.

Taking into account the listed requirements, the decision was made to use a multigraph for mathematical modeling, which is a composite of multiple graphs mapping different properties of railway infrastructure elements.

4. ETCS APPLICATION MODEL

The ETCS application model in the Multigraph IS is highlighted in the form of a layer $L^3(IS)$. The sets formed by the ETCS application layer include the following IS elements:

- $V^{11}(IS)$ – balise,
- $V^{12}(IS)$ – balise groups,
- $V^{13}(IS)$ – ETCS area boundaries,
- $V^{21}(IS)$ – radio block center,
- $V^{23}(IS)$ – LEU coders,
- $E^{8}(IS)$ – the succession of balise groups for the normal direction,
- $E^{9}(IS)$ – the aftermath of the balise,
- $E^{15}(IS)$ – linking a group of balise and the first balise in the group,
- $E^{16}(IS)$ – linking the switchable balise and the signal,

- $E^{17}(IS)$ – the link between a group of balise and a signal, and
- $E^{18}(IS)$ – the neighborhood of balise groups for the opposite direction.

The deployment model of ETCS equipment allows the identification of the locations of interactions between the trackside subsystem and the on-board subsystem. It is necessary to complement this model with the content of exchanged telegrams and messages in order to fully map these interactions. Given the flexibility of the structure I, it would be possible to model the information structure in terms of vertex color. However, it seems that such an approach would overcomplicate the model. Therefore, in IS at a higher level of generality, the functions of the balises are realized by the groups that are defined by $V^{11}(IS)$. On the other hand, the detailed content of telegrams and messages is stored in the model in the form of the corresponding attributes of the vertices $V^{12}(IS)$ modeling balises.

Another group of relationships mapped by IS for the ETCS application is the functional relationships between its various elements. The model of these relationships is used in the detailed verification of the ETCS application. In the current form of IS, the following subgraphs of functional links are defined:

- The link between the group of balise $V^{11}(IS)$ and the first balise $V^{12}(IS)$ models an edge of color 15 $E^{15}(IS)$:

$$IS^{15} = (V^{11}(IS) \cup V^{12}(IS), E^{15}(IS)). \tag{1}$$

- The link between a switchable balise $V^{11}(IS)$ and the signal $V^{4}(IS)$ models an edge of color 16 $E^{16}(IS)$:

$$IS^{16} = (V^{12}(IS) \cup \ V^{4}(IS), E^{16}(IS)). \tag{2}$$

- The link between balise group $V^{12}(IS)$ and the signal $V^{4}(IS)$ models the edge of color 17 $E^{17}(IS)$:

$$IS^{17} = \left(V^{11}(IS) \cup \ V^{4}(IS), E^{17}(IS)\right). \tag{3}$$

5. EXAMPLE OF MULTIGRAPH IS

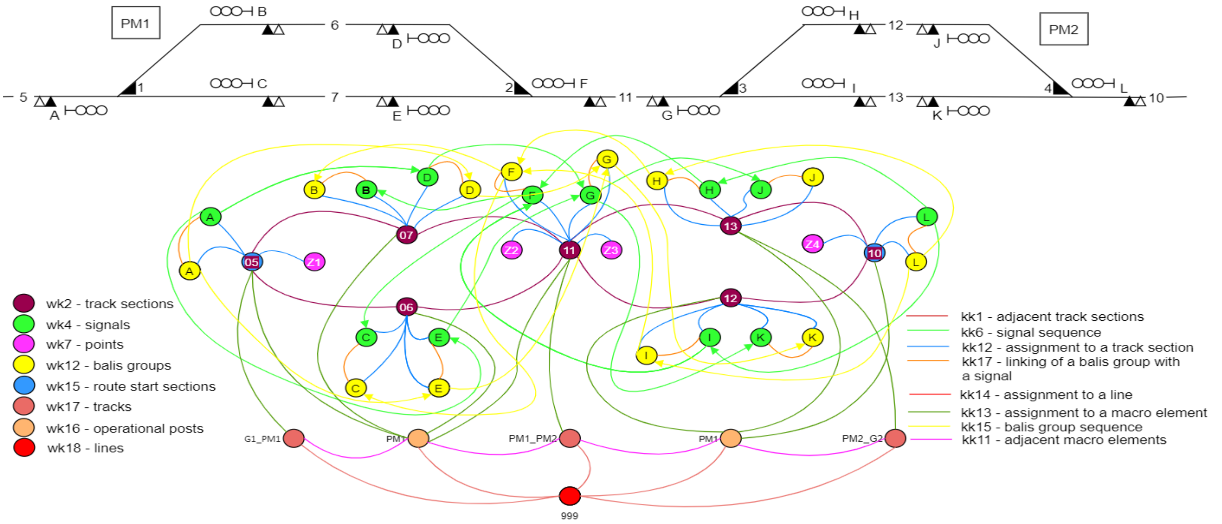

Fig. 1. Example of Multigraph IS for a simple track layout (source: own development)

Fig. 1 shows a graphical representation of an example of Multigraph IS for a simple track layout – specifically, a section of a single-track railway line (no. 999), where two stations with passing functionality (PM1 and PM2) have been organized. The track layout of each station consists of two points and two main tracks: main and additional tracks (1, 7, 12, and 13). Between the stations – and from the stations to the boundary of the area – there are track sections forming routes 5, 11, and 10. Each point is equipped with a controlled switch (1, 2, 3, and 4). There are main signals (A, F, G, and L) at the station entrance on both sides. At stations, the exit to the track is protected by main signals (B, C, D, E, H, I, J, and K). A group of balises is installed at each signal, with a switchable balise associated with the signal.

To a limited extent, Fig. 1 illustrates the topology layer $L^1(IS)$, the functional infrastructure layer $L^2(IS)$, and the ETCS application layer $L^3(IS)$.

The topology layer L^1 consists of

$$L^1(IS) = \{V^2, V^{15}, V^{16}, V^{17}, V^{18}, E^1, E^{11}, E^{13}, E^{14}\}, \tag{4}$$

where:

- $L^1(IS)$ – topology layer,
- $V^2(IS)$ – track sections,
- $V^{15}(IS)$ – initial sections of train routes,
- $V^{16}(IS)$ – operational points,
- $V^{17}(IS)$ – trails,
- $V^{18}(IS)$ – railroads,
- $E^1(IS)$ – the proximity of track sections,
- $E^{11}(IS)$ – the neighborhood of the macro model element,
- $E^{13}(IS)$ – affiliation with the macro model, and
- $E^{14}(IS)$ – railway affiliation.

For the example ETCS area, the individual vertex sets have the following elements:

- $V^2(IS) = \{5,6,7,10,11,12,13\}$,
- $V^{15}(IS) = \{5,10\}$,
- $V^{16}(IS) = \{PM1, PM2\}$,
- $V^{17}(IS) = \{PM1\_PM2, G1\_PM1, PM2\_G2\}$,
- $V^{18}(IS) = \{999\}$.

The functional infrastructure layer $L^2(IS)$ consists of

$$L^2(IS) = \{V^2, V^6, E^{12}\}, \tag{5}$$

where:

- $L^2(IS)$ – functional infrastructure layer,
- $V^4(IS)$ – signals,
- $V^6(IS)$ – switches, and
- $E^{12}(IS)$ – track section affiliation.

For the example ETCS area, the individual vertex sets have the following elements:

- $V^4(IS) = \{A, B, C, D, E, F, G, H, I, J\}$ and
- $V^6(IS) = \{1,2,3,4\}$,

The ETCS application layer $L^3(IS)$ consists of

$$L^3(IS) = \{V^{12}, E^{12}, E^8, E^{17}\}, \tag{6}$$

where:

- $L^3(IS)$ – ETCS application layer,
- V^{12} – balise groups,
- $E^8(IS)$ – the sequence succession of balise groups for the normal direction, and
- $E^{17}(IS)$ – the link between a group of balise and a signal.

For the example ETCS area, the individual vertex sets have the following elements:

- $V^{12}(IS) = \{A, B, C, D, E, F, G, H, I, J\}$.

The formal ETCS application model is used in the next chapter, so its elements are described in more detail. The whole application model comprises a layer $L^3(IS)$. A layer defines the sets of vertices and edges that make up the model. For the purposes of this article, some simplifications have been made. The components of an ETCS application are only modeled by vertices representing groups of balises.

There are no distinguished components of balises. The modeling of LEU encoders has also been abandoned. Their functionality is implicit in the direct relationship between the balise group and the signal. In the definition of $L^3(IS)$ edge types modelling the relationships between model elements are indicated. These can be refined using elements of the Multigraph IS metamodel. In the first case, it is the consequence realization. In this case, for two groups of balises $gb1, gb2 \in V^{12}$, we will write $N^8(gb1, gb2) = 1$. The second case includes the functional dependence between a group of balises $gb \in V^{12}$ and a signal $s \in V^4$, which we denote $F^{17}\{gb, s\}$.

6. RULES FOR VERIFYING THE CORRECTNESS OF THE ETCS APPLICATION

6.1. Virtual prototyping

Models of the structure of the digital twin of the ETCS application provide the basis for the implementation of the ETCS Application Virtual Laboratory [12]. The virtual laboratory provides such services as rapid and flexible development of the ETCS application design documented in an appropriate manner and full verification of the consistency and correctness of the cooperation of on-board and trackside equipment of ETCS applications. The first objective is achieved using innovative virtual prototyping technology (WPAE).

The virtual prototyping of ETCS applications is an innovative approach to the design of ERTMS/ETCS system applications on a given area of the railway network. The virtual prototyping process is based on the following assumptions:

- it is fully digital,
- it uses a digital description (digital model) of the environment, including a digital description of the railway infrastructure,
- it uses modeling and simulation,
- it uses a standardized format for the digital description of railway infrastructure (RailML),
- it follows the WPAE algorithm,
- it automates the creation of fixed elements of ETCS applications, and
- it verifies the correctness of the ETCS application design in real time.

The WPAE algorithm defines the successive stages of ETCS application development. The stages do not form a rigid sequence, but moving to the next stage is dependent on meeting certain requirements. The WPAE algorithm consists of the four stages of work on the model: specifying the model version, area modeling, modeling the environment, and ETCS application modeling.

The algorithm in the form of a BPMN diagram [13] is shown in Fig. 2.

As mentioned earlier, virtual prototyping involves a close link between modeling and the verification of the correctness of the model. The expected result of such an approach is automatic. Up-to-date information about the correctness of the model is provided as the real-time updated status of the ETCS application design/model. Determining this status is a complex operation at the stage of the solution development process since the model at that time passes through various intermediate states, in which the occurrence of inconsistencies is a natural state. The fast processing of the model is possible thanks to its representation in the form of Multigraph IS. Verification algorithms moving through the multigraph check define correctness conditions, which apply to all the layers presented earlier. Examples that are discussed further are the verification of the relative position of the entry signal and warning shield for the functional infrastructure layer of the national railway system and the verification of the distance limits between groups of balises in the ETCS application layer.

6.2. Verification of the position constraints of balise groups

The ERTMS/ETCS system specification [14-16] specifies requirements for the minimum and maximum distance between different groups of balises. The minimum distance between those groups is derived from the minimum distance of the nearest two balises coming from adjacent groups. This distance is measured between the reference marks (remarks) of these balises [14]. The distance between groups of balises for the purpose of linking succession (linking) is measured differently.

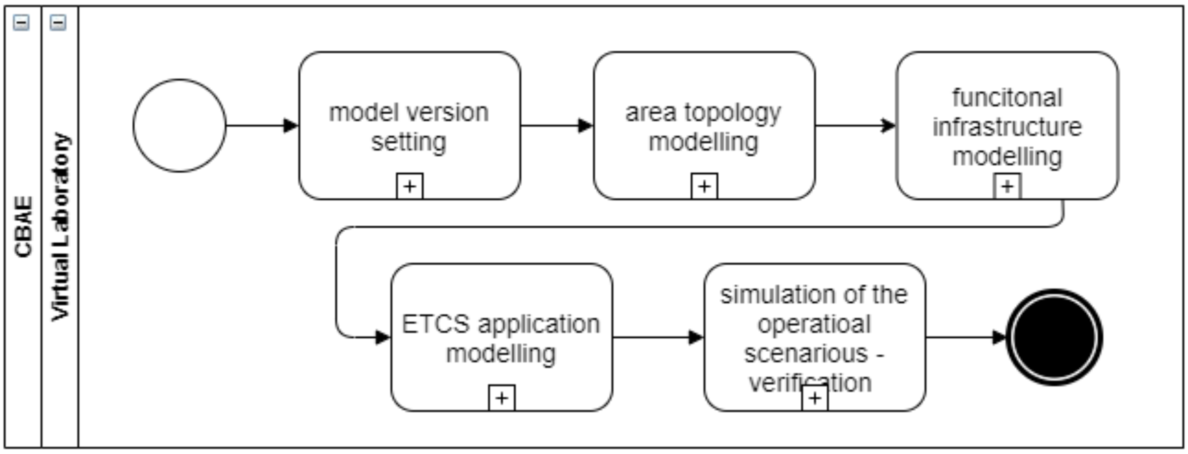

Fig. 2. Virtual prototyping process (source: own development)

The difference should be described as the distance between the first two balises in these groups for which N_PIG = 0. The property described in this section takes into account the former principle. The parameters of the mission profile are determined by the maximum distance between groups of balises, which is 2500 m.

The accuracy of these criteria of these features/characteristics can be defined by the minimum distance between groups – 3 m ($Vmax$ < 300 km/h) – and the maximum distance between groups – 2500 m.

The integrated criterion formally formulated is

$$\bigwedge_{v,w,x\in V^{11}} \bigwedge_{p,r\in V^{12}} N^9(v,w) = 1 \wedge F^9(x,p) = 1 \wedge P^{20}(v,p) = 1 \wedge P^{20}(w,r) = 1 \wedge N^8(p,r) = 1 \wedge IS.Vmax = 300 \Longrightarrow IS.D(v,w) \geq 3 \wedge IS.D(x,w) < 2500. \quad (7)$$

For any balise v, w, x – and for any group of balises p, r – such that v and w are neighbors, x is the first balise in group p, balise v belongs to group p, balise w belongs to group r, and groups p and r are neighbors. Thus, there is a relation: the distance between w and v ≥ 3, and the distance between x and v < 2500.

The algorithm verifies the property by processing the following IS subgraphs:

- IS^8 - the succession of groups of balise in the direction of travel and
- IS^{15} - linking a group of balise and the first balise in the group.

6.3. Verification of the assignment switchable balise to the signal

A balise is a trackside transponder responsible for the transmission of telegrams containing packs in ETCS language to or from an ETCS-equipped train passing over it (i.e., at a specific point). Balises provide point-to-point interactions with trains passing over them. In the system specification, we can distinguish two types of balises: switchable and non-switchable. The telegrams transmitted by a switchable balise can change over time. This change is triggered by signals from the basic layer of the CCS equipment. The LEU encoder is an indirect circuit responsible for processing these signals. Based on the analysis of the signals, the existing traffic situation is sent to the train via LEU-generated telegrams. These telegrams are then sent to the switching balises via the "C" interface. The currently installed ERTMS/ETCS system in Poland uses the measurement of electric signals in the signal circuit.

In the described version of the ETCS application model, a simplification has been introduced that omits the physical LEU encoder. It is additionally enforced by defining the assignment of a balise group containing switchable balises directly to a signal whose indications are reproduced in the telegrams sent to the train.

The correctness condition for the described configuration should check that each group of balises containing a switchable balise is assigned a signal whose indications are the basis to generate the corresponding telegram.

The formal notation of this condition is as follows:

$$\bigwedge_{p\in V^{12}} \mathrm{p.is\_switchable()} = 1 \bigvee_{s\in V^{6}} F^{17}\{p,s\} = 1 \ \wedge IS.D(p,\mathrm{s}) = 8[\mathrm{m}] \tag{8}$$

The above condition can be read as follows: Each balise p that is a switchable balise has a functional relation with a signal s, and the distance between s and p should be 8 m. The relation effect between is dependent on the effect of which is to generate a telegram corresponding to the current indication of the signal.

6.4. Verification of balise linking

In order to ensure the consistency of the configuration of the balise group layout in ETCS, linking sequences (linking) between balise groups are introduced. According to [14], this is done to:

- determine whether a balise group has been missed or was not found within the expectation window and take the appropriate action,
- assign a coordinate system to balise groups consisting of a single balise, and
- correct the confidence interval due to odometer inaccuracy.

The consecutive link ensures that a train cannot move into the ETCS area without confidence that all balises have correctly transmitted the data to the train. Starting from the first balise enabling the transition into the ETCS area, the balises transmit information about the location of successive groups of balises that the ETCS-equipped train will pass as it continues according to the movement authorization. Groups of balises indicating a temporary speed restriction (TSR) are ignored.

If, in a given ETCS application, it is assumed that balise groups are linked, the following condition must be fulfilled: Inside the ETCS area, all balise groups that do not realize the TSR function must be connected. The formal notation of this condition is as follows:

$$\bigwedge_{p\in V^{12}} \mathrm{p.is\_TSR()} = 0 \bigvee_{s\in V^{12}} F^{8}(p,s) = 1\ . \tag{9}$$

The above condition can be read as follows: For every group of balise p that is not a group specifying a temporary speed limit, there is a group of balise s that is linked to group p.

7. CONCLUSIONS

Digital solutions for railways place high demands on the correctness of the description of railway infrastructure. Currently, research is being conducted in many commercial and academic centers to standardize various aspects of the infrastructure models. At the same time, the required increase in the accuracy of models is causing a significant increase in their complexity due to the amount of data and the greater scope for information. Therefore, it is important that the created models are of a formal, mathematical nature. When this condition is met, algorithmic model processing is possible. By using algorithms implemented in the form of computer programs, it is possible to check the model using validity criteria. The paper uses examples to show how to formally formulate the correctness conditions for the design of CCS systems and, in particular, the ETCS application layer. It was found that the formal form of the model is ready for algorithmic processing. This result gives hope for the development of fast algorithms for model verification (e.g., through a virtual prototyping process).

It should be noted that the structure of the Multigraph IS proposed in this article is an effective structure of data describing the railway infrastructure, including the ETCS application. Owing to its polymorphic properties, it is a flexible concept that allows the consistent modeling of any aspects of the real system. By allowing a formal description of the railway infrastructure for a given area, it provides a mathematical model that allows a formal definition of the correctness criteria, which represents the technical engineering design rules of the ETCS application and its environment. Applied solutions from the field of graph theory allow the development of effective algorithms for model verification. The digital design of an ETCS system is similar, at least in terms of its content, to a signaling plan with a self-verification function.

Work on the project "Digital railway. Digital twin of ETCS application - Virtual prototyping and simulation of operational scenarios" is coming to an end, but the results of the project are already finding their way into further research. Applications for funding are currently being formulated for two new projects related to the digitalization of railways and verification of the model through simulation of operational scenarios, as well as model verification using concurrent automata.

Funding

This research was funded by Warsaw University of Technology within the Excellence Initiative: Research University (IDUB) program.

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Received 07.04.2022; accepted in revised form 31.08.2023