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MODELING OPERATIONAL SCENARIOS FOR A HIGH-SPEED SIGNALING SYSTEM

Summary. In railway signaling, operational scenarios are integral to the system modeling process, serving to outline expected use cases and define the behavior of the system, subsystems, and actors within the railway environment. Operational scenarios are a primary source of requirements for developing the train control system and its subsystems. Additionally, the design of operational scenarios can offer invaluable insights for arranging trackside assets and may influence the creation of instructions and operational procedures for railway staff. This article highlights the advantages of defining operational scenarios in the early stages of implementing train control systems based on the European Train Control System application level 2 for high-speed lines. The process of defining and modeling operational scenarios is illustrated by analyzing a selected, representative scenario.

1. INTRODUCTION

Operational scenarios are an integral part of signaling system development. They are used to specify expected use cases and define the specific behavior of the signaling system or parts of it. Moreover, they are frequently used as a source of requirements for developing future signaling systems. Additionally, the use of operational scenarios can provide invaluable conclusions regarding the organization of trackside equipment and may influence the creation of operating instructions and procedures for personnel associated with the operation of rail traffic.

This article highlights the advantages of defining operational scenarios at the early stages of a signaling system based on the European Train Control System (ETCS) application level 2 (L2) for high-speed railway lines. The process of defining and modeling operational scenarios is illustrated by presenting selected representative aspects of operational scenario modeling.

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2. RELATED WORKS

An operational scenario model is desired to represent system behavior in specific railway traffic situations. Some authors have concentrated on the simulation of specific ETCS devices using state machines and Simulink software [2, 5, 10, 14]. These works present the internal interactions of a system compliant with the ETCS specifications [16, 17]. They also present interactions between system components that produce specific functionalities of the whole system. These models mostly use finite state machine modeling to present transitions between states of the system or its components. Such defined interactions are modeled in software that can provide automatic validation and verification against the occurrence of deadlocks and other undesirable system behaviors. Such modeling can be used to validate the correctness of system operation by the manufacturer and to demonstrate compliance with the ETCS specifications.

Another branch of the modeling and simulation of signaling systems with the ETCS is papers that show the influence of TS configuration or railway line parameters, such as medium speed or capacity. These articles focus on the creation of a mathematical model that can determine the best configuration of devices for a specific railway line. The selection criteria may differ depending on the needs of a specific infrastructure manager and the purpose of the railway line. For example, it may be the maximum speed of travel or the line capacity. Such models allow for a more conscious definition of expectations for systems installed on railway lines. However, they do not define operational rules, focusing on maximizing the profits from the investment in the rail traffic control system. Examples of such publications are [2, 3, 11, 13, 15, 18]. Some of these papers present the usage of dedicated software, such as RailSys [1].

Also, some papers have concentrated on very specific topics, such as breaking curve calculations [9]. Such work uses very specialized models and software. The results are very detailed and lead to the optimization of the specific aspects of the rail system rather than the specification of new functionalities or operational scenarios.

In his publication [8], Andrzej Kochan presented the theoretical foundations of the digital twin of the ETCS application. His proposed modeling method focuses on presenting the ETCS trackside application without presenting the relationships between other components included in the rail traffic control system. The theoretical foundations presented by the author may constitute the basis for further consideration and development, for example, by presenting operational scenarios.

Leading manufacturers of the ETCS, such as Siemens, Hitachi, and Alstom, create operational scenarios as a development element of new ETCS applications on railway lines. The operational scenarios they create are prepared with devices from a specific manufacturer in mind, which is why these scenarios differ at least partially from each other in detailed ways. These scenarios are part of the project and are not publicly available. The authors of the article cannot assess possible internal methods of describing operational scenarios used in companies developing ETCS-compliant systems.

3. ETCS L2 ON HIGH-SPEED RAILWAY LINES

When considering the ETCS L2 on high-speed lines, it is important to identify the possible signaling configuration. As a signaling configuration, it is understood as a combination of trackside signaling (TS) optical signals and ETCS marker boards (MBs) in the context of the ETCS L2 implementation. Two types of MBs can be distinguished: ETCS stop marker boards (SMBs) and ETCS location marker boards (LMBs).

The most important difference is that:

- ETCS stop markers shall be used to:
  - unambiguously identify an end of authority (EOA), which must not be overpassed without authorization from the signalman and which may protect one or a group of safety-critical points such as a point switch, a conflicting route, an entrance of a station, junctions, etc.

   - identify specific locations on the track that the train shall not overpass when a movement authority (MA) is not available unless the driver has received specific authorization from the signalman.
- ETCS location markers are to be used to:
   - unambiguously identify an EOA that does not protect a safety-critical location.
   - identify specific locations on the track where the train shall stop when running without an MA if the driver has received specific instruction from the signalman.

The signaling configuration can be defined on behalf of a matrix, as shown in Table 1.

Table 1
Signaling configuration definition

	Trackside equipment		ETCS L2	Comments
	Station area / signaling post	Open track		
0	TS	TS	None	Independent or as part of national class B system.
1	TS	TS	ETCS L2 as an overlay on the traditional, basic control command and signaling (CCS) equipment	No ETCS marker boards needed. The operating trains may or may not have on-board ETCS equipment.
2	TS	TS + LMB	ETCS L2 as a part of the operational optimization process	The traditional block is divided into intermediate ETCS blocks. The operating trains may or may not have on-board ETCS equipment.
3	TS	LMB	In the station: ETCS L2 as an overlay on the traditional, basic CCS equipment Open track: Only ETCS MB	The basic operational process is only for ETCS L2 trains. The traditional signaling system is used only as a backup.
4	SMB	LMB	ETCS L2 is fully implemented; no traditional TS	The operational process is used only for ETCS L2 trains. An SMB on open track can be used (i.e., before a tunnel or other specific location).
5	SMB	LMB (SMB in specific locations)		
6	SMB + LMB	LMB (SMB in specific locations)		

According to rows 3–6 in Table 1, two types of MBs are considered. As mentioned in [**Błąd! Nie można odnaleźć źródła odwołania.**], there are two types of MBs: (a) ETCS stop markers and (b) ETCS location markers.

In the analysis, for which the authors are providing Centralny Port Komunikacyjny Sp. z o. o. (CPK) with a special purpose vehicle (SPV) to build HS lines in Poland, Configurations 3, 4, 5, or 6 (in Table 1) are taken into consideration.

In Table 1, there is no configuration considering LS and MB in the stations or signaling posts, although the railway industry is considering this type of implementation as a theoretical solution.

Apart from the abovementioned problems, there is an aspect in the differences in what is shown on a trackside signal in comparison to what is displayed on the driver machine interface (DMI). This aspect is especially important for Configurations 2 and 3 as well as for Configurations 4-6 on the border between a line equipment in TS and a line only with MBs.

The most important thing is that, from a traditional signaling point of view, the aspect directing into a line without trackside signals should be a stop aspect. However, from the perceptional point of view, a red aspect should not be passed under any circumstances. That is why some countries are implementing specific solutions. Some of these are shown in the examples below:
- No specific signal aspect but a special "CAB" marker board, informing that only cab signaling provided trains shall move after it (i.e., Switzerland, Netherlands) [**Błąd! Nie można odnaleźć źródła odwołania.**];
- An additional aspect that indicates the proceed aspect for ETCS L2 trains and the stop aspect for non-equipped trains (i.e., blue on red signal; Spain) [12];
- The signal intentionally turns dark (Germany).

4. OPERATIONAL SCENARIOS AND THEIR PART IN ETCS IMPLEMENTATION

The operational scenarios used in signaling are a type of document describing the behavior of the system in specific operational situations. The purpose of creating them is to indicate how the system should behave in each situation. Operational scenarios can be divided into three main context groups in terms of described situations:
- Normal situations are operating situations with no system failures and the appropriate procedural behavior of the operating personnel
- Degraded situations are operating situations that arise in the event of system failures or non-compliant behavior of service members.
- A maintenance situation is an operational situation in which the system and personnel operate differently from what is normally required due to system maintenance activities.

A scenario consists of parts:
- Initial state: the assumed initial conditions.
- Sequence of events: a description of the sequence of events, which can be presented as a list of consecutive events or information flow diagrams.
- Intermediate state: an optional form of a final state for an event, which is also the initial state for a subsequent event. It is mainly introduced in complex scenarios.
- Final state: the final state after all events included in an operational scenario have occurred; sometimes also describes the conditions for continued operation after a given sequence of events has taken over.
- Comments: some scenarios may require comments to occur, which may include:
  - A description of a different possible behavior of the system in case certain events of the main sequence occur in a different order than described, or additional events occur.
  - Additional conditions required for any of the events described in the main sequence of events to occur.
  - References to another scenario. Each scenario describes only the sequence of events associated with a given in order to obtain a complete scenario; it is sometimes necessary to juxtapose several scenarios together [7].

Operational scenarios can take different forms of expression. Diagrams, verbal descriptions, and tables seem to be the most common. Sequence diagrams can also be identified, in which the flow of information within the system is shown by assigning individual actions to specific parts of the system.

Additionally, illustrations are often used as part of the scenario to aid in understanding it. Usually, these illustrations relate to the track situation.

The sources of origin of operational scenarios can vary. Examples of the use of operational scenarios include defining the signaling system with ETCS behavior in various operational contexts to cover ETCS trackside behavior that is not defined by the ETCS standard. The design of the scenarios is most often influenced by railway traffic regulations and expected operation in normal, degraded, and maintenance contexts.

The scenarios described in this article are intended to shape operational rules. In addition to this, they are intended to define the contracting authority's requirements for those tendering for the planned train control system.

5. MODELING OPERATIONAL SCENARIOS FOR A HIGH-SPEED SIGNALING SYSTEM

5.1. Operational scenarios formal specification

In [8], Andrzej Kochan proposed a formal description of ETCS application scenarios, which can be enhanced to the level of a signaling system.

In the present work, the authors use a system compliant with RCA-CPK (Reference CCS Architecture – Centralny Port Komunikacyjny), which consists of several layers:

- TMS (train management system) – Management, control, and management layer – includes functions for planning transport, constructing traffic charts, implementing transport plans and timetables, managing and controlling traffic, in particular: dispatch control, transferring information about trains, automatic route setting, remote control.
- APS (advanced protection system) – Safety and aggregation layer – includes functions related to safety, in particular: dependency control, processing of commands and reports critical for safety, mapping objects in the form of abstract elements, and processing dependency equations.
- DEV (devices) – Executive layer of vehicle and trackside devices – includes direct control of devices and physical devices and objects (e.g., sensors, trains, switches).
- GEN (generic functions) – General functions layer – includes functions that interact with each layer (e.g., diagnostics, operator stations, system access authorization, system configuration management, application data entry, power supply, track system topology data management). The general functions layer is not relevant in operational scenarios.

Each scenario shall serve as a representation of one specific railway traffic event, for example, leaving the train station. Another very important scenario description is preliminary and final conditions. These conditions describe when the scenario shall occur and what the final goal is, which shall be achieved when the scenario is carried out as planned.

Between preliminary and final conditions, there is a sequence of events, which describes all events, activities, and decisions that take place in the scenario.

An operational scenario can also be described using a mathematical formula:

$$\boldsymbol{OS = \{ES, PC, SE, FC\},}$$

where:
OS – operational scenario
ES – environment specification
PC – preliminary conditions
SE – sequence of events
FC – final conditions

Environment specification is described in Chapter 5.2. Preliminary conditions can be expressed as tuples with the following properties and events:

PC = {TMS-PAS.cond, SMN.cond, TMS-PE.cond, APS-IXL.cond, APS-MT.cond, DEV-VD.cond, ATP-OB.cond, DRV.cond }

Similarly, final conditions can be expressed as tuples with the following properties and events:

FC = {TMS-PAS.cond, SMN.cond, TMS-PE.cond, APS-IXL.cond, APS-MT.cond, DEV-VD.cond, ATP-OB.cond, DRV.cond }

In both formulas, each component's conditions are represented by a set of properties – states and events:

- **TMS-PAS.cond –** traffic management system – planning system conditions of the module responsible for the management of operational plan; examples of possible events being preliminary conditions: *TMS-PAS.OP_generation*
- **SMN.cond** – Conditions given by a signalman; example of a possible event: *SMN.setting_a_route*

- **TMS-PE.cond** – traffic management system – plan execution conditions given by a module responsible for operational plan execution; example of a possible event: *TMS-PE.command_a_signal*
- **APS-IXL.cond** – advanced protection system – interlocking conditions given by module responsible for interlocking; example of a possible event: APS-IXL.route_set
- **APS-MT.cond** – advanced protection system – movement authority transactor conditions given by module responsible for ETCS L2; example of a possible event: APS-IXL.MA_send
- **DEV-VD.cond** – devices – vehicle devices conditions given by a train; example: DEV-VD.v – velocity of the train
- **ATP-OB.cond** – automatic train protection conditions of ETCS on-board equipment; example of a condition: ATP-OB.mode, which depicts the current mode
- **DRV.cond** – driver conditions; an example condition is DRV.Start_selected, which represents event of driver selecting Start on DMI
- **EXT.cond** – external conditions implied by systems outside of the system under consideration.

The set of conditions used in operational scenarios and their descriptions shall be a part of those scenarios' documentation.

The set of events, decisions, and actions required to achieve final conditions when starting from preliminary conditions is the sequence of events. This sequence can be expressed as:

$$SE = \{e_1, e_2, \ldots, e_n\},$$

where:
$\mathbf{e_n}$ – event number n,
n – number of all events.

A set of parallel events shall be expressed with the AND operator, and a set of exclusive events based on a particular decision shall be expressed with the OR operator:

$$SE = \{e_1, e_2, OR(\{e_3, e_4\}, \{e_5, e_6\}), \ldots, e_n\}.$$

A single event can be expressed as:

e (event.type, event.actor, event.activity)

where:
event.type – type of event, whether it is an activity or action,
event.actor – actor of an event – module of signaling system,
event.activity – activity taken by an actor in an event.

5.2. Environment specification

Operational scenarios depend highly on the environments in which they take place. They differ depending on the possibilities provided by this environment and its configuration. Additionally, in scenarios involving transitions with other, outside signaling systems, the functions provided by those systems are limited. There is a need to provide an additional description of the operational scenario, which provides this additional information, resulting in variants of the scenario. The authors defined the following environment specifications:

- **SIG.conf** – signaling configuration, as stated in Chapter 3,
- **ETCS.conf** – ETCS configuration, including configuration of National Values and additional configuration specification, for example, the usage of specific release speed or additional functions, such as automatic train ahead free (ATAF),
- **EXT.conf** – external signaling system, which is relevant in scenarios including border transitions.

ES = {SIG.conf, ETCS.conf, EXT.conf}.

5.3. Graphical representation of an operational scenario

Following [8] and combining all previously presented considerations, an operational scenario can be expressed as in Fig. 1.

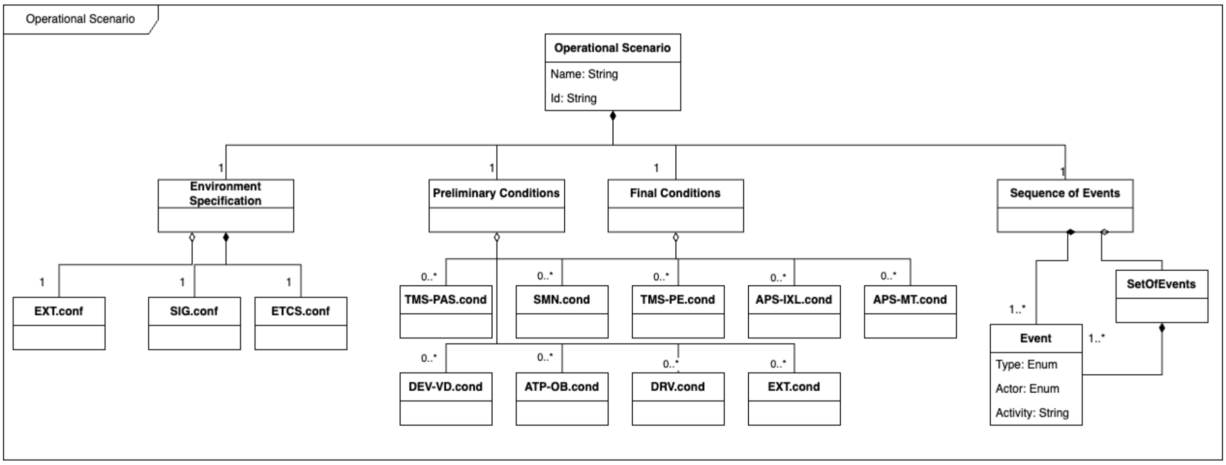

Fig. 1. Components of an operational scenario (own study)

The authors propose using graphical methods to present operational scenarios being modeled, providing more friendly and readable descriptions. Moreover, graphical representation ensures that fewer mistakes and errors will occur. The proposed way to describe an operational scenario is to use Unified Modeling Language (UML) activity diagrams with actor pools.

Another way to present an operational scenario graphically is with a UML sequence diagram, which can be useful for describing information sharing between actors. This diagram cannot replace an activity diagram, but it shall be treated as supplementary to it.

The authors propose establishing a process in which operational scenarios are initially modeled using graphical solutions, and then a formal description shall be provided. In the future, it may also be possible to create tools that, based on an operational scenario model description, might generate its graphical representation.

5.4. Operational scenario simulations

Simulation of operational scenarios must take into account all previously stated formal model descriptions and place them on a specific configuration of a part of the railway system to carry out the whole scenario. Such a specification may be expressed as [8] shown at Fig. 2.

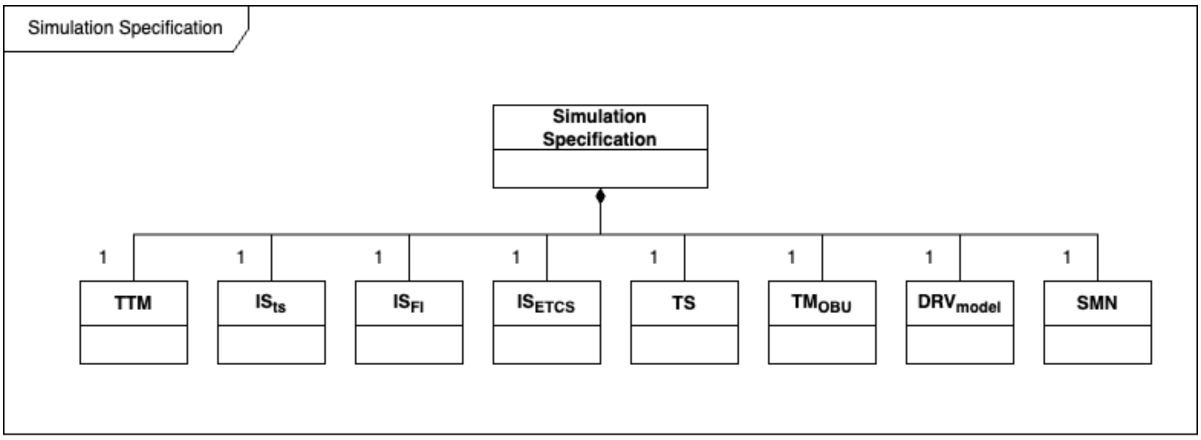

Fig. 2. Components of simulation specification (own study)

$$SS = \{TTM, IS_{ts}, IS_{FI}, IS_{ETC}, TM, TM_{OBU}, DRV_{model}, SMN_{model}\},$$

where:
SS – simulation specification,
TTM – timetable model,
IS_{ts} – infrastructure – trackside network model,
IS_{FI} – infrastructure - functional infrastructure model,
IS_{ETCS} – infrastructure – ETCS specific application
TM – train model
TM_{OBU} – ETCS on-board model
DRV_{model} – driver model
SMN_{model} – signalman model

With such a defined simulation specification, it is possible to verify whether the prepared operational scenario is compliant with the overall ETCS Specification [16] and the specifications of each module. Additionally, simulations can provide information about deadlocks and areas where possible bottlenecks or safety hazards may occur. Another valuable output from the simulation is information about the overall impact of the operation scenario on the railway system, including its foreseen capacity and average speed.

There are multiple ways to simulate operational scenarios. Generally, there are two possible ways to simulate an operational scenario:

- Using methods of formal verification – formal verification is the process of checking whether the designed system meets certain requirements (properties) using a formal mathematical method. One of the possible methods is to use the timed and asynchronous model.
- Using specialized software, it is also possible to simulate a signaling system to gather limited but highly specialized results. An example of such a simulation may be RailSys, which is software specialized in modeling railway traffic.
- Using a simulated environment – these methods include setting up an environment consisting of physical or software-simulated devices and actors. These are the devices and actors in the model presented in the article constituting SS. Such methods provide information on how the whole system will behave in a specific scenario. Such simulations are very expensive because they must use developed (or not fully developed but operational) modules, and they may be used in late development verification.

The process in which operational scenarios are simulated and the results of this simulation are evaluated, leading to model verification, are beyond the scope of this paper. Such simulations and verifications are future research topics. However, the process in which an operational scenario and its simulation can be defined, and its results are presented in Fig. 3.

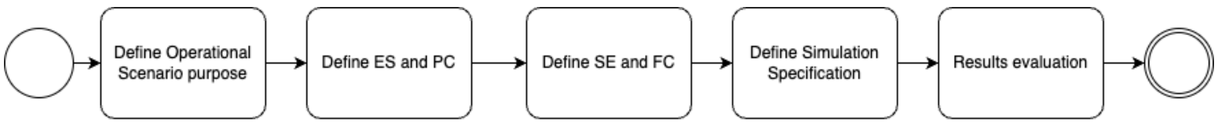

Fig. 3. Operational scenario consideration process (own study)

6. REPRESENTATIVE SCENARIO MODEL

One scenario that represents the presented method was selected to present the method of modeling operational scenarios. Namely, the scenario presenting the entry into the final train station in configuration was chosen.

7. CONCLUSIONS

This article presented a proposal for an operational scenario model for a high-speed signaling system. It presented the operational scenarios of signaling systems, including what they consist of, the types of scenarios that can be distinguished, and where they are applicable. Various possible configurations of high-speed signaling systems were also presented. Also, the article presented a formal way of presenting an operational scenario with a specification of a simulation environment that could be used for scenario research and validation. The authors presented selected aspects of a representative operational scenario used in the development of high-speed signaling systems. Table 2 is showing representative scenario definition.

Table 2

Representative scenario definition

ES - Environment Specification	SIG.conf = (without physical signals, W ETCS 10 in stations) ETCS.conf = (typical set national values, SvL (supervised location) on EoA (end of authority) location) EXT.conf = (non-applicable)
PC - Preliminary Conditions	DEV-VD.cond = vehicle on track tracks moving towards a traffic control post ATP-OB.cond = on-board devices in full supervision (FS) mode TMS-PAS.cond = generated operational plan covering the final station
SC - Sequence of Events	e_1 – (action, TMS-PE, request to set the entry route) e_2 – (action, APS-IXL, set the entry route) e_3 – (action, APS-MT, generate and transmit MA FS (movement authority – full supervision) corresponding to the set route) e_4 – (action, ATP-OB, receive MA EoA (movement authority – end of authority) location change) e_5 – (action, DEV-VD, train arrives at the traffic control post) e_6 – (action, APS-IXL, release of the last line block section) e_7 – (action, APS-IXL, detection of the correct sequence of train entry into the last section of the route) e_8 – (action, DEV-VD, stop the train on the station tracks) e_9 – (action, ATP-OB, reports position after stopping) e_{10} – (action, APS-MT, receive a position report after stopping) e_{11} – (action, APS-MT, send the MA shortening to the front of the vehicle) e_{12} – (action, TMS-PE, receive the updated MA and shorten EoA to the front of the train) e_{13} – (action, TMS-PE, after a specified time, the route is terminated by the train)
FC - Final Conditions	DEV-VD.cond = vehicle is standing in front of the exit indicator ATP-OB.cond = on-board devices in full supervision (FS) mode ATP-OB.cond = end of authorization (EoA) shortened to the front of the train

This article presented the benefits of using an approach focusing on operational scenarios as the main source of requirements for the high-speed railway traffic control system and confirmed the validity of such an approach in the development of a railway control system.

The approach of defining the operational scenarios describing operational use cases and behavior of the signaling system presented in the article is used as a key requirement source in the development of operational scenarios for high-speed signaling in Poland, where ETCS L2 without signals is planned, and one issue is the transition between the networks of PKP Polskie Linie Kolejowe S.A. (with signals) and CPK (an area without signals).

Aspects related to verifying the correctness of operational scenarios using various types of simulations were considered in this article and will be the subject of future research by the authors.

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