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Issues of safety of autonomous railway operation at the GoA3 and GoA4 level

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ABSTRACT: This contribution discusses the issue of approaching safety issues for newly introduced autonomous rail vehicle operation systems with the GoA3/GoA4 automation level. In particular, the paper discusses the issue of normative requirements for establishing and demonstrating safety requirements that are in place today for railway systems. The paper seeks to define the minimum criteria or processes that should be met and demonstrated in order for autonomous train operation to be accepted as sufficiently safe for commercial operation.

KEYWORDS: Automatic train operation (ATO), Grade of automation (GoA), rail transport

I. INTRODUCTION

This paper focuses on the analysis of the safety requirements and processes needed for the adoption of autonomous operation on conventional lines. In order to ensure a sufficient level of safety, it mainly discusses the normative framework, the methods of proving safety and the minimum criteria that must be met for the acceptance of such systems in commercial operation.

In recent years, autonomous train control has developed significantly and is becoming a key element in the modernization of rail transport. While autonomous operation has already been successfully implemented in urban rail systems according to EN 62290-1 [1], its application on conventional lines still poses a significant technological and safety challenge. The transition from a controlled urban environment to operations with a higher variability of conditions, such as level crossings, heterogeneous infrastructure and mixed traffic, places extreme demands on the implementation of safety and control systems.

A key part of this evolution is the integration of technologies such as Automatic Train Operation (ATO) and European Train Control System (ETCS), which enable automated train control while maintaining interoperability and a high level of safety. Although these technologies cover critical functions, it is necessary to comprehensively assess and demonstrate the safety level of autonomous operation, especially on conventional lines with high operational risks.

According to current regulatory requirements, safety objectives must be defined for each system and their fulfilment must be demonstrated by quantitative and qualitative methods. Therefore, in an environment of autonomous operation on conventional lines with automation levels GoA 3 and GoA 4, it is crucial to adapt proven safety management principles known from urban systems to open infrastructure. This includes not only the correct definition of safety requirements, but also the definition of processes and criteria for their validation and independent assessment.

II. ANALYSIS OF THE LEGISLATIVE AND NORMATIVE ENVIRONMENT

This paper focuses on the issue of autonomous operation of trains on conventional or high-speed railway lines. It concerns the operation of autonomous vehicles without a driver, which is usually referred to as the GOA3/GOA4 automation level. This designation is introduced in IEC62290-1:2014 [1], but this standard is specified for Urban Guided Transport Management System (UGTMS), i.e. for different environments and conditions of use. There is already a long experience (almost 20 years) with the implementation of UGMTS in GoA3/GoA4 and their operation, and certainly some of the experience gained in this area can be used. However, there is currently no similar standard for use in conventional or high-speed rail environments that comprehensively addresses the requirements for autonomous operation of these types of railways. In the railway environment, the generic standards of the CENELEC EN 50126-1 ed.2 [2], EN 50126-2 [3], EN 50129 ed.2 [4] or EN 50128 ed.2 [5] series are applied. The railway system in EU countries applies a systemic approach to safety management in the form of EU directives and regulations, in particular Directive (EU) 2016/798 of the European Parliament and of the Council of 11 May 2016 on railway safety [6] and the resulting Commission Implementing Regulation (EU) No 402/2013 of 30 April 2013 on a common safety method for risk assessment and evaluation. [7] These standards are mandatory for railway systems but not for urban systems, which are excluded from the scope of these directives and regulations and their application may be voluntary.

In the Czech Republic, the basic conditions for the operation of railways and rail vehicles are defined by Act No. 266/1994 [8], on Railways, as amended. This law allows autonomous operation only on special railway tracks (e.g., metro), which to some extent reflects European practice, where autonomous operations are more common in urban systems. The adoption of autonomous operations on conventional railway lines would require changes to the legislative framework and compliance with strict safety requirements.

Unlike UGTMS, where the carrier is also the infrastructure operator, conventional rail is a liberalised market where transport services are provided by different carriers while the infrastructure is managed by a government organisation. A specific area is sidings, which are not subject to interoperability requirements and may have different safety standards. Establishing a uniform safety strategy is difficult in this environment because multiple stakeholders with different interests - be they economic, technical or operational - are involved.

III. DEFINITION OF AUTONOMOUS OPERATION SYSTEM

In order to deal with the risk analysis of the considered autonomous railway system, the system, its architecture, functions and interfaces must first be defined. According to CENELEC EN 50126-1, these issues are addressed in Stage 1 (Concept) and Stage 2 (System Definition). These stages must not be underestimated because without a good consideration of the scope and function of the system, a good list of risks and resulting safety requirements cannot be developed. These Life Cycle Stages should be developed primarily by the system operator, possibly in collaboration with contractors. This is realistically the first major practical problem, as in the current carriers and operators of railway systems, the procedure according to this standard is not implemented in a systematic approach to the design or operation of railway systems. [2]

For the purposes of this paper, the definition of an autonomous operation system is not the primary objective, but it provides a necessary basis for understanding what components and influences need to be considered when applying risk analysis methods. This brief description is not intended to create a detailed, specific or precise overview of an autonomous system, but rather to roughly outline the issues and to emphasize that risk analysis must cover all of the following elements of the system.

The operational environment of an autonomous system may include, for example:

- The operating environment of the autonomous system includes factors and influences from the environment that may pose a security risk:
- Natural hazards: trees near the track, landslides, weather conditions such as dense fog or heavy rain.
- Unexpected obstacles: fallen branches on the tracks, animals on the track.
- Human activity: movement of people on the track, vandalism, trespassing.
- Traffic at level crossings: Risk of train-vehicle collisions at level crossings.

For example, conventional railway line infrastructure includes:

- Railway line: track alignment, directional and height parameters of the line, line branching.
- Signalling infrastructure: Signalling systems, level crossing protection, points, ETCS track-side elements, etc.
- Communication systems: Data links between the line and trains, GSM-R used for both ETCS and ATO train protection, other communication means
- Power system: Electrical infrastructure for train operation

The autonomous rail vehicle is equipped with a number of components that ensure its safe and efficient control. [9, 10] Examples of the essentials are:

- Train protection: all components of the ETCS OBU
- Autonomous Decision Module (ADM): the unit responsible for autonomous train control, sensor data analysis and real-time decision making
- Automatic driving module: automatic driving itself, reaction to the timetable, energy efficient braking under traction, ideal braking curve
- Perception module (perception of the environment): a set of sensors for obstacle detection and perception of the environment:
- LIDAR, cameras, radar, ultrasonic sensors, etc.
- Navigation and localization systems: GPS, inertial units and digital map bases, ETCS localization (packages)
- Communication units: GSM-R communication terminals,
- Train control systems

Current technologies used in railway operation, such as infrastructure signalling equipment or ETCS, are based on many years of experience and will undoubtedly be part of the technological background for autonomous train operation. At the infrastructure level, automated traffic management systems such as automatic track alignment and ATO (Automatic Train Operation) are expected to proliferate. On the vehicle side, ETCS OBUs and on-board ATO systems will play a key role. However, a fundamental change is expected on the rail vehicle side, which must be equipped with technologies replacing the driver's activities. The safety requirements for these systems are not yet clearly defined, which creates a challenge for their certification and operational approval. Current safety standards for rail vehicle control systems (e.g. traction converters, braking systems) correspond to SIL 2 according to CENELEC EN 50126-2 and CENELEC EN 50129 ed. 2 [3, 4], provided that their operation is supervised by a driver who intervenes in the event of non-standard situations. However, in the context of autonomous operation without a driver, the safety requirements and RAMS parameters of these systems will have to be reassessed, which requires a detailed risk analysis and the definition of appropriate measures.

IV. DIFFERENT REQUIREMENTS FOR AN AUTONOMOUS RAILWAY VERSUS AN AUTONOMOUS METRO SYSTEM

UGTMS systems in GoA3/GoA4 mode have been in place in the world for more than 20 years. Therefore, it would seem that one can build on the design and experience gained in a number of real-world applications. In practice, this transfer is very difficult as a number of risks associated with the different nature of operation and conditions of use of the system (in a driverless application) need to be addressed. In this section the main requirements for the operation and safety management of an autonomous rail traffic system compared to an autonomous UGTMS system are presented and discussed. [1]

A. Infrastructure and environmental conditions

Open vs. enclosed track space

- Autonomous metro is typically operated in confined spaces (e.g., underground or elevated railways) where conditions are controlled and predictable (strictly defined routes, controlled stations, no interaction with other means of transport). This means that automated systems can concentrate on fewer variables, making them easier to implement.
- Autonomous rail moves in a more dynamic and less controlled environment. Interaction with other vehicles (such as other trains, vehicles at a level crossing, trucks or people) is common on the railway. This means that an autonomous system must be equipped with advanced detection technologies to constantly monitor not only the track, but also potential obstacles such as animals, technical faults or other trains.

B. Control and communication systems

Advanced traffic management

- On an autonomous railway, there is a need to address complex traffic management where trains meet on different tracks and interact with other trains. This includes the need for coordination between autonomous trains and rail traffic management, which is much more complex than on the metro, where trains tend to operate in a closed loop.

- Autonomous rail therefore requires advanced communication systems (e.g. GSM-R, ETCS - European Train Control System) for communication between the train and the control room or between trains. In contrast, an autonomous metro can rely on a local, closed communication infrastructure that is not as prone to failures or signal loss.

Signal assurance and track monitoring

- On rail, real-time track monitoring needs to be ensured as various unexpected situations can occur - such as signal failures, track damage, accidents or blockages. An autonomous system must be able to react to changes and safely avoid these problems, which requires powerful sensors and intelligent algorithms that can detect obstacles over long distances.
- In contrast, the environment is much less variable in an autonomous metro, which means that systems are easier to predict and do not require as extensive detection technology.

C. High speeds and complex track conditions

High speeds

- Autonomous rail must operate at much higher speeds than an autonomous metro. This poses challenges for obstacle detection and real-time decision making. The higher the speed, the less time to react in case of danger. An autonomous train needs to be able to detect and avoid dangerous situations over greater distances, while ensuring that even at these high speeds it is possible to stop or react in time.

Unpredictable weather and environmental factors

- Problems caused by adverse weather (snow, rain, ice) can occur on the railway which can affect track stability or the performance of train systems (for example, trains can derail due to slippery tracks). Autonomous rail systems need to be robust to these conditions, which may include advanced weather monitoring or adaptive control.

D. Interaction with other means of transport

Interaction with other trains

- An autonomous railway cannot do without cooperation with other trains on the line. Advanced train interval management and ensuring that the autonomous train does not interfere with other trains on the same line is needed for effective traffic management. In the event of emergencies such as delays or train failures, the autonomous system must make an autonomous decision to stop or reroute the train safely. The use of different combinations of train paths for traffic management must be considered.
- For UGTMS autonomous systems, safety requirements focus primarily on a clearly defined mode of operation where trains do not interact with other vehicles. On an autonomous railway, it is necessary to assume the introduction of mixed operation of trains without and with autonomous mode, which is not common in UGTMS systems. [1]

Level crossings and coexistence with vehicles

- Autonomous rail will often have a need to interact with vehicular traffic, particularly at level crossings. This includes the need to ensure that the autonomous train responds to blockages of the crossing by vehicles or people. Also, the autonomous system needs to be equipped to communicate with other transport components such as traffic systems and emergency services in the event of a failure. [11, 12]

E. Emphasis on safety standards and interoperability of the EU rail system

Safety standards for the autonomous railway

- Comparable safety standards based on CENELEC 50126 are used for UGTMS autonomous systems. As this standard is procedural and thus does not define any specific requirements for the design and operation of the railway system, the quality and safety management process must be applied throughout the life cycle of the railway system, regardless of the specific nature and operating conditions. These must be defined within the different life cycle stages, which will specify the requirements of the autonomous railway system compared to the UGTMS. [1, 2]
- Railways in the EU have to comply with the European directives on interoperability (mainly applicable to state-owned infrastructure but can also be applied to privately owned railway infrastructure). This implies a very demanding process of defining a single standard for all EU Member States, on which there must be uniform compliance, and which must be applied throughout the EU. This process is currently underway in the framework of the Europe's Rail project.
- EU railway systems must apply Directive (EU) 2016/798 of the European Parliament and of the Council, which includes requirements for each railway undertaking, infrastructure manager and maintenance entity to use the monitoring methods set out in the Common Safety Methods (CSM-RA). The Directive also introduces Common Safety Targets (CST) and Common Safety Indicators (CSI) to ensure and demonstrate a high level of safety on the railway. These methods must also be applied to autonomous operation and the achievement of these safety targets must be demonstrated for EU railways.

F. Risk analysis for the autonomous railway

High risk in a more complex environment

- Autonomous railways have to address a broader spectrum of risks compared to autonomous UGTMS. Risk analyses need to be conceived in a significantly more complex way considering the nature of the operation.
- Risk analysis will be more complex on an autonomous railway than on a stand-alone UGTMS system. Both technical failures and traffic dynamics (obstacles on the track, signal failures, collisions with other trains and vehicles) need to be considered. This requires extensive analysis of possible scenarios, including simulations, and the implementation of measures to eliminate these risks.
  - Detection and response systems
- Given the dynamics of the environment, autonomous railways must include advanced detection systems that can not only detect obstacles on the track but also predict dangerous situations (e.g. collisions with other vehicles, system failures). This means deploying high-level sensors and algorithms for predictive driving. [13-15]

V. REPLACEMENT OF DRIVER FUNCTIONS BY AUTONOMOUS SYSTEMS

The fundamental change between the current railway control and safety systems and the autonomous driving system under consideration (at GoA level 3 and 4) is mainly the replacement of the human factor (driver) in the control function of the railway vehicle. Therefore, it is important for the autonomous system to analyse in detail the driver's functions related to the function of driving an autonomous vehicle on the railway, both in order to define the functional requirements of the autonomous system and to demonstrate that the autonomous system will be safer than the current approach using a driver. [16, 17]

A. Analysis of the main activities and responsibilities of the driver

It is assumed that the autonomous system must fully assume the responsibilities of the driver. However, the question is how to define and, in particular, how to demonstrate the requirement for a level of assurance of the reliability and safety of the functions previously performed by the driver. The driver plays a key role in ensuring the safety of driving a railway vehicle. According to the Guidance Note on the Recognition of Examiners and other standards, his responsibilities include the following activities:

Key responsibilities of the driver [18]

1. Driving of traction vehicles:
- Control of speed and compliance with signal instructions.
- Recognising and responding to changes in infrastructure (e.g. deteriorating adhesion conditions).
- Ensuring smooth and safe driving.
2. Responding to emergency situations:
- Identifying and responding to obstacles on the track.
- Dealing with vehicle or infrastructure failures.
- Emergency stopping of the train in crisis situations.
3. Communication and interaction:
- Regular transfer of information with the control room.
- Informing passengers in the event of an emergency.
4. Safety check:
- Monitoring the integrity of the train (doors closed, vehicle condition check).
- Compliance with operating rules and safety standards.
- Intuitive diagnosis of rail vehicle function (unusual vibration, noise, smell, etc.).

B. Risks associated with the human factor

The driver has a key role in the current system, the reliable and safe performance of which is often affected by a number of factors:
- Human error: misinterpretation of signals or slow reaction.
- Fatigue, stress, ill health: Long shifts can lead to reduced attention and increased error rates.
- Constraints in crisis situations: Time to make decisions is often critical and misjudgement can occur.
- Driver overload: Particularly in critical situations, one may find oneself unable to correctly assess critical information and perform adequately to ensure safe driving.

Autonomous operation on the railway should be able to eliminate these risks associated with the human factor, but it must also be verified that this does not create other risks.

C. Comparison of the safety of human driving and autonomous systems

According to the basic risk acceptance approach used for safety relevant systems, any new system should be equally or safer in relation to safety. However, it is clear that a simple comparison with known human reliability and safety parameters may not be sufficient to meet this requirement. In the case of the human agent, its failure is judged from different perspectives (in particular, proving medical and professional competence) which will not be applicable to the failure of autonomous systems which are assumed to be faultless, i.e. will not fail. Clearly, the legislative and legal implications of the potential failure of autonomous systems on the railway will need to be worked out. Autonomous systems at GoA level 3 and 4 should eliminate the risks associated with the human factor, but also present new technical challenges in terms of proving their safe and reliable operation.
- Technical reliability: autonomous systems can respond faster and more accurately thanks to redundancy and algorithms.
- Elimination of human error: eliminating factors such as fatigue and misinterpretation of signals.
- Challenges in crisis situations: Algorithms must be able to deal with unknown scenarios without human intervention.

VI. RISK ANALYSIS IN AUTONOMOUS RAILWAY OPERATION

To determine the safety of the operation of the autonomous railway, it is necessary to follow the quality, reliability and safety management process defined by CENELEC EN 50126-1 ed.2. In this section, the safety management process will be discussed especially in the key part of stage 3 - risk analysis. Risk analysis is a key process in determining the safety requirements of autonomous railway operation. The risk analysis has to be carried out on the basis of the conception and definition of the system (Stage 1 and Stage 2), which should be developed by the main stakeholders, i.e. in particular the user/operator of the intended system, i.e. in the case of railways the infrastructure manager and the railway undertaking (CENELEC EN 50126-1 defines the term "Railway Undertaking"). [2-5]

CENELEC EN 50126-1 specifies a structured approach to risk analysis that includes the following steps:

A. Identify and classify hazards

- Includes the identification of all potential hazards that may directly or indirectly lead to losses (injury to passengers, employees or the public, environmental damage or commercial losses) during the operation and maintenance of autonomous railway operations;
- Identify the causes that, in combination with human errors or operating conditions, may result in losses;
- Identify the control measures that are in place to control or limit the occurrence of any adverse event whose associated risk is unacceptable;
- Predictable hazards shall be systematically identified in the application environment to include not only normal but also system fault and emergency conditions;
- Hazard classification shall be based on the probability of occurrence and severity of consequences. At a minimum, individual hazards shall be classified into those that are associated with a generally acceptable risk and those that are not considered generally acceptable. Hazards that are associated with a generally acceptable risk do not need to be further analysed, their entry in the hazard record is sufficient;
- Calibration of the risk matrix
    - Frequency of occurrence of the risk: Quantification of the probability of the event.
    - Severity of Consequences: Evaluation of the impact of events on operations and safety.
    - Risk Acceptance Category: Defining the risk acceptance area according to the ALARP principle.

Proper calibration of the risk matrix is essential to adapt the process to the specific conditions of autonomous operation where the driver is not present as a witness and competent authority.

B. Select the risk acceptance principle

Three basic approaches can be used for risk acceptance:
- Code of practice: Use of best practices and operational standards.
- Reference system: Comparison with systems with a similar level of automation that are already operating safely.
- Explicit risk assessment:
    - Qualitative approach: Subjective risk assessment based on experience.
    - Use of ALARP, GAMAB and MEM methods

- Quantitative approach: calculation of risks using mathematical models
- Definition of THR (Tolerable Hazard Rate) values.

C. Define and apply risk acceptance criteria

- Establish criteria according to the ALARP (As Low As Reasonably Practicable) method that minimizes risks to an acceptable level.
- Use other approaches such as GAMAB (Globalement Au Moins Aussi Bon) or MEM (Minimum Endogenous Mortality)
- For a quantitative approach, define the THR (Tolerable Hazard Rate) for each safety function.

D. Assess risks

- Identify adverse events:
  - Events leading to losses such as personal injury, environmental disruption or commercial losses.
- Identification of causes:
  - Technical failures (e.g. failure of a system element)
  - Human error
- Identification of control measures:
  - Measures currently in place to reduce the likelihood of an adverse event.
- Risk estimation:
  - Quantitative estimation of the frequency of adverse events and their consequences.
  - Identification of the need for risk reduction and design of additional measures.
- Determination of additional measures:
  - Implementation of measures to reduce the risk to an acceptable level.
- Document the analysis:
  - Create a document containing the methodology, assumptions and data used. [19, 20]

E. Establish an ongoing risk management process

- Document the methodology, assumptions and data used.
- Periodic reassessment of risks throughout the system life cycle.

The entire risk analysis process, which is outlined in CENELEC standards EN 50126-1 and EN 50126-2 and is also captured in the CSM-RA Unified Safety Method [7], provides a structured framework for the identification, assessment and management of risks throughout the life cycle of a railway system. However, this process requires a skilled and comprehensive approach by the infrastructure manager and railway undertakings, including the system supplier/manufacturer and the organisations maintaining the system.

In the introduction of autonomous operation on rail, the main difficulty now is how to demonstrate sufficient safety of the system, which is not yet experienced in rail operations, nor is there a defined legal and legislative framework. It is clear that everybody responsible for the railway, including all other stakeholders, must find a consensus, particularly on the calibration of the risk matrix and the choice of methods and criteria for accepting risks. The latter is crucial for a given level, as it directly determines whether the identified risks will be accepted as generally acceptable or will be subjected to a more detailed process leading to the application of mechanisms to steer their impacts to a generally acceptable level and will be the basis for the safety requirements in the system requirements specification.

The calibration of the risk matrix can be based on the risk classification of existing systems. For example, statistical values based on the EU Railway Safety Directive 2016/798, which introduces Common Safety Indicators (CSIs), can be used and to accept sufficient safety, CST safety targets can also be used. These indicators are usually the output of a systematic record of incidents that is compulsorily kept by both infrastructure managers and operators. The use of these data, within which it should be possible to identify the individual causes of failures (losses) in the existing railway system, is certainly one of the fundamental bases for setting up a risk analysis process to demonstrate the level of safety of the autonomous railway system and is a necessary condition for the subsequent phase of risk acceptance and acceptance.

Unfortunately, neither national nor EU legislation defines a list of risks or criteria for their acceptance in the EU railway system. It is therefore necessary for each entity involved in the safety issue to ensure, in accordance with the requirements of CENELEC standard EN 50126-1) the setting of the parameters of the risk analysis process, including the criteria for acceptance and acceptance of risks. Only in this way can the detailed issues related to the identification of hazards and the resulting risks of an autonomous process on the railway in a driverless application be pursued, which should make it possible to set the safety requirements of the system in the first place, but at the same time allow them to be demonstrated as sufficiently safe. [21]

VII. CONCLUSION

In this paper, the issue of safety for newly introduced systems of autonomous operation on railways with automation level GoA3/GoA4 according to CENELEC EN 62290-1 was discussed. Although a number of commercial applications at the GoA3/GoA4 level have been successfully operated in the field of UGTMS for a number of years, the paper shows that a direct transfer of these systems to the railway is not entirely feasible because autonomous railway operation differs in a number of technical and operational differences that have a major impact on the risks associated with its operation. The article also discusses the legislative and normative aspects of the risk analysis process that must be respected and fulfilled in the case of a railway system. In particular, the key process is the issue of the risk analysis process, within which the issues of setting up the whole process (especially the calibration of the risk matrix and the setting of risk acceptance criteria) must be addressed for a system that has not yet been systematically implemented on the railway, nor have the appropriate legislative measures for the introduction of autonomous operation on the railway been defined. Addressing this issue is crucial to be able to demonstrate a sufficient level of safety, which must be demonstrated at the level of the whole system (not just the rail vehicle), which requires a comprehensive solution to safety issues both by the infrastructure manager and the operators and also together with technology suppliers/manufacturers and system maintainers.

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