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LEGAL FRAMEWORK AND INFRASTRUCTURE FOR THE OPERATION OF AUTONOMOUS TRAINS IN THE SLOVAK REPUBLIC

Abstract. This paper examines the legal framework and technical readiness for the deployment of autonomous train operation in the Slovak Republic. While the European Union has established a harmonised system of interoperability and safety supported by Technical Specifications for Interoperability (TSI), the Fourth Railway Package and the ATO over ETCS concept, national legislation in Slovakia remains largely oriented toward a traditional model of train operation with a dominant human role. The study identifies the key legal gaps that must be addressed, including the redefinition of responsibilities between drivers and automated systems, the adaptation of safety assessment procedures, and the introduction of cybersecurity requirements. The paper also analyses the current state of railway infrastructure in Slovakia, highlighting significant disparities between modernised core corridors and technologically outdated regional lines. The findings show that the successful introduction of autonomous trains will require comprehensive infrastructure upgrades, including full implementation of ETCS Level 2 or higher, the transition from GSM-R to FRMCS, and the modernisation of signalling and communication systems. The study concludes that autonomous train operation in Slovakia is feasible, but its implementation depends on coordinated legislative, technical and organisational development aligned with European standards.
Keywords: Autonomous train operation, Interoperability, Legal framework, Automation in rail transport

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Introduction

The ongoing digitalisation of railway transport and the development of automated train control systems are gradually shifting the rail sector from traditional train driving towards higher levels of automation, up to fully autonomous operation. Over the past decade, the European railway environment has increasingly focused on the implementation of harmonised technical standards, particularly the European Train Control System (ETCS), which forms the technological basis for autonomous train operation.

However, the introduction of autonomous trains requires not only technological progress but also an appropriate adjustment of the legal framework and the adaptation of railway infrastructure. The aim of this paper is to analyse the current state of legislation and the technical base of the railway infrastructure in the Slovak Republic and to identify the key challenges that must be addressed before autonomous systems can be implemented.

1. Current Legal Framework in the Slovak Republic and the European Union

The legal framework of railway transport in the Slovak Republic is closely aligned with the European system of interoperability, safety, and technical requirements for railway infrastructure and rolling stock. The core national legislation is Act No. 513/2009 Coll. on Railways, which establishes the conditions for the operation of railway infrastructure and rolling stock, safety rules, supervisory competences, and the general technical requirements for the Slovak railway system. Important legislation also includes Act No. 514/2009 Coll. on Railway Transport, which defines operational rules, the obligations of railway undertakings, personnel qualification requirements, and liability structures related to train operation. In the context of autonomous trains, its provisions will need to be adapted to the new distribution of responsibilities between the train driver and automated control systems. (Pažítková, 2024)

A key component of European railway legislation is the Technical Specifications for Interoperability (TSI), which define harmonised technical and safety requirements for individual subsystems of the European railway system. For the analysed subject, the most relevant TSIs include:

- TSI INF – defines infrastructure parameters such as track geometry, structural elements, line capacity and design constraints;
- TSI CCS – regulates control, command and signalling systems, including ETCS implementation and GSM-R communication. This specification is crucial for automation and autonomous train operation;
- TSI ENE – defines the parameters of the energy subsystem, traction power supply and compatibility of energy systems;
- TSI OPE – covers operating rules, staff competences, communication procedures and operational safety principles at both national and international levels;
- TSI LOC&PAS and TSI WAG – set technical and safety requirements for passenger and freight rolling stock;
- TSI SRT – defines safety requirements for railway tunnels, including risk control, evacuation procedures and safety equipment;
- TSI TAP and TSI TAF – regulate telematic applications for passenger and freight transport and the exchange of operational data between railway undertakings and infrastructure managers. (Pažítková, 2024; European Union Agency for Railways, n.d.)

The European legislative framework is further strengthened by the technical pillar of the Fourth Railway Package, which introduces centralised vehicle authorisation and safety assessment procedures carried out by the European Union Agency for Railways (ERA). The harmonisation of rules and technical standards provides the basis for the large-scale introduction of automated train operation, as interoperability is a key prerequisite for reliable autonomous systems. (European Commission, n.d.; European Union Agency for Railways, 2020)

In the context of autonomous trains, TSI CCS plays a decisive role, as it defines the requirements for the implementation of ETCS Level 2 and above, GSM-R and future FRMCS communication infrastructure, as well as interoperability interfaces necessary for automation. Available research shows that autonomous train operation in Europe must be compatible with the concept of ATO over ETCS, which enables automated train operation while maintaining the European safety framework. (Costa & Villalba, 2018; ERTMS Belgium, n.d.; Kontron, n.d.)

Both national and European legislation provide a foundation for the future introduction of autonomous train control systems, although further legal adjustments will be required—particularly in the areas of safety assessment, operational rules and the regulation of the interaction between the train driver and automated systems.

1.1. Levels of Automation and Legal Implications

The concept of autonomous railway operation is directly connected to the level of automation achieved in train control systems. Over the past decade, European railway policy has increasingly promoted automation as a means of improving safety, efficiency and interoperability, particularly through harmonised signalling systems such as the European Train Control System (ETCS) (European Union Agency for Railways, n.d.; European Commission, n.d.).

Automation levels range from conventional manual driving, through driver-assisted operation, to fully autonomous train operation. In the European context, the concept of Automatic Train Operation over ETCS (ATO over ETCS) defines a framework for gradually increasing automation while preserving compatibility with the European safety architecture (Costa & Villalba, 2018; ERTMS Belgium, n.d.).

From a legal perspective, current railway legislation remains oriented toward a traditional operational model in which the train driver holds primary responsibility for train movement and safety. This model is deeply embedded in national railway laws and technical regulations, which explicitly assume the presence of a human operator as the final authority in operational decision-making (Pažítková, 2024).

As automation progresses toward driverless and unattended operation, the legal framework faces fundamental challenges. Responsibility begins to shift from individuals toward infrastructure managers, manufacturers and system designers who define algorithms, operational logic and system safeguards (Pažítková, 2024).

However, legal regulations have not yet sufficiently clarified how responsibility should be distributed in cases where operational decisions are executed automatically.

2. Necessary Amendments to the Legal Framework for Autonomous Train Implementation

The introduction of autonomous trains represents a major technological shift that must be reflected in the legal framework governing railway operations. Although current legislation is based on a harmonised European safety and interoperability system, many national laws and technical regulations still assume a "traditional model" where the train driver plays a central role. Autonomous train control systems change the distribution of responsibilities between humans and technology, requiring new legislative definitions, procedures and safety requirements. (Pažítková, 2024)

The first area requiring legislative revision involves the redefinition of the roles of the train driver, railway undertaking and infrastructure manager. Current legislation assumes the presence of a train driver responsible for train movement, reaction to signals and decision-making in exceptional circumstances. For autonomous trains, these responsibilities must be redefined. (Pažítková, 2024)

The second area concerns safety assessment and certification. Although European legislation includes Common Safety Methods (CSM) and risk assessment procedures (Regulation (EU) 2018/762), autonomous systems introduce new risk scenarios that are not yet explicitly addressed and will need to be integrated into the regulatory framework. (European Union Agency for Railways, 2020; Pažítková, 2024)

A third necessary area relates to cybersecurity, as autonomous trains depend heavily on digital systems, remote communication and data exchange—significantly more than conventional trains with onboard staff. (Kontron, n.d.; European Union Agency for Railways, 2020)

Finally, operational rules will need to be updated. These rules currently assume direct driver interaction with signalling equipment, visual monitoring of the track, acknowledgement of signals and handling of emergency events. (Pažítková, 2024)

For these reasons, the successful introduction of autonomous trains will require a comprehensive legal framework that integrates technological, safety and operational requirements and clearly defines the competences of all involved entities. Amendments to the legal framework will form an essential pillar of the technical modernisation of the railway system.

3. Current Railway Infrastructure in the Slovak Republic

The railway infrastructure of the Slovak Republic comprises an extensive system of lines, signalling and safety systems, energy and communication subsystems that form the technical foundation for train operation at the national level. The infrastructure manager is Železnice Slovenskej republiky (ŽSR), which annually publishes data on the state of the network. As of 31 December 2023, the network comprised approximately 3,630 km of railway lines, of which 1,585 km (44%) were electrified. Single-track lines constitute the majority of regional lines, while double-track lines are mainly located on core corridors. (Pažítková, 2024)

Railway infrastructure includes a significant number of engineering structures. The ŽSR network contains 2,326 bridges, 2,065 level crossings, and 78 tunnels with a combined length of nearly 48 km, along with other elements ensuring operational continuity. These structures require extensive maintenance and upgrades, particularly on aged or mountainous sections. (Pažítková, 2024)

Various categories of signalling and safety equipment support the safe and continuous operation of trains. Their technical condition significantly affects operational reliability and the potential for digitalisation.

A key element of the modern command-and-control system is the GSM-R communication network, used for data and voice communication between the driver and the traffic control centre. As of 2023, it consisted of one central controller and 64 base stations (BTS). GSM-R coverage is essential for the deployment of advanced safety systems such as ETCS Level 2 and represents an important step toward digitalisation and automation. The network also includes extensive operational communication systems and information technology components. (Pažítková, 2024)

Investment activity in 2023 reached almost €366 million, mainly targeted at corridor modernisation, speed upgrades, renewal of signalling equipment and compliance with TSI requirements. (Pažítková, 2024)

These facts indicate that the Slovak railway infrastructure is undergoing gradual modernisation, although significant regional disparities remain. Core corridors already implement technologies compatible with European standards, while many regional lines still require upgrades to signalling systems and communication infrastructure. These conditions will strongly influence the feasibility and pace of autonomous train deployment.

4. Necessary Infrastructure Modifications for Autonomous Train Operation

The introduction of autonomous trains in Slovakia requires substantial technological and organisational adjustments to the existing railway infrastructure. Although corridor modernisation has progressed in recent years, the current technical level is not yet sufficient for full autonomous operation. The transition to autonomous control depends primarily on the availability of high-quality signalling, communication, energy and information systems, as well as on improved interoperability readiness.

The most critical prerequisite is the full implementation of ETCS Level 2 or higher, which enables continuous train position monitoring and provides the conditions for ATO over ETCS. Large sections of the Slovak network still use outdated signalling systems with limited capabilities; therefore, modern electronic interlockings and line-side systems with reliable data interfaces will need to be deployed. (European Union Agency for Railways, n.d.; Costa & Villalba, 2018)

Another key area is communication infrastructure. While GSM-R is being gradually deployed, the increasing demands of autonomous operation make it necessary to transition to FRMCS (Future Railway Mobile Communication System). FRMCS will provide higher data throughput, lower latency and greater reliability—essential attributes for autonomous operation, especially on high-speed or high-density lines. (Kontron, n.d.)

Autonomous systems will also require changes in infrastructure maintenance planning, traffic management organisation and harmonisation of national technical standards with TSI requirements. The success of autonomous systems in Slovakia will depend on the modernisation of regional lines, the pace of digitalisation and the ability to integrate new technologies into existing traffic management systems.

5. Discussion and Conclusion

The deployment of autonomous trains is a complex process requiring coordinated progress in legislation, infrastructure and traffic management technologies. The analysis shows that the European safety and interoperability framework provides a solid foundation for future autonomous operation, but its implementation in Slovakia will require significant amendments. National legislation is predominantly oriented toward the "traditional model" of train driving, where the human factor plays a dominant role. (European Commission, n.d.; Pažítková, 2024)

The technical level of Slovakia's railway infrastructure is also uneven. While core corridors comply with modern European standards, many regional lines still feature outdated signalling and communication systems. Autonomous operation requires the implementation of advanced technologies, primarily ETCS Level 2 or higher, GSM-R or FRMCS, and modernised signalling and communication systems. Without these, sufficient safety and reliability cannot be guaranteed. (Pažítková, 2024; European Union Agency for Railways, n.d.; Kontron, n.d.)

The discussion on the future of the Slovak railway system and the introduction of autonomous trains must also consider broader implications. Autonomous operation may significantly transform work organisation, traffic processes and economic models. At the same time, it offers opportunities to increase line capacity, reduce energy consumption and optimise traffic management. The benefits of autonomous trains can only be fully realised in an environment prepared from legal, technological and operational perspectives.

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