21. Increase Safety in Regional Networks with Decentralization – The Autonomous Route Setting Approach

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21.1. Introduction

The rail sector is in change to improve efficiency by increasing the number of trains traveling over certain distances in less time. However, this push for efficiency comes with significant risks, particularly in safety-critical tasks that are performed manually, which increases the likelihood of human error. To mitigate these risks, the use of assistance systems is recommended, especially in regional areas where control centers oversee larger regions and cannot monitor every event with equal precision.

The main challenge is to provide support that enhances safety without interfering with the workers' tasks. One of the most critical areas where support can be provided is in route setting [1, 2]. However, centralized planning for large areas presents difficulties, especially when systems need to dynamically adjust train routes due to delays, disruptions, or to resolve potential conflicts. The complexity lies in managing future track capacities without compromising safety while ensuring a continuous flow of trains.

To address this challenge, the Europe's Rail project R2DATO aims to develop innovative approaches to achieve the goal of full automation and autonomy in rail operations. The authors propose an Autonomous Route Setting (AnRS) approach, which resolves potential conflicts in a decentralized manner, with each switch making decisions independently. If necessary, these switches can communicate with other AnRS systems in the area to effectively resolve complex conflicts. A key advantage of this approach is that it can be integrated into the existing infrastructure without requiring changes to current systems and interfaces.

In this extended abstract, the authors will introduce dependent systems, relevant roles, and then discuss the differences between automatic and autonomous route setting. They will explore the concept of autonomy, defining the criteria that characterize an autonomous system. The abstract will also summarizes anomaly detection to protect server infrastructure from unauthorized access and demonstrate how this concept can be applied to the railway sector. Finally the authors will derive the architecture for the AnRS system, explain its functionality, and show how this system could be demonstrate and tested. The abstract will close with an outlook on the next steps in its development.

21.2. Fundamentals

In the following the authors will described the systems that are directly related and associated with the AnRS approach. This chapter will describe the basics for understanding the AnRS functionality, how it can be embedded into the existing infrastructure and how it can be differed from the Automatic Route Setting (ARS). Further it will be explained how autonomy is defined and how this concept can be applied to the railway domain.

21.2.1. Traffic Management System and Automatic Route Setting

Rail networks in general have centralized control centers where signalers or computer systems manage train movements (see Figure 1). One central system is the Traffic Management System (TMS). The core components of a TMS can be broadly categorized into different key areas. Firstly, train scheduling and timetabling form the foundation, where the system plans and manages the schedules of trains, optimizing the allocation of train paths and timings to balance demand and infrastructure capacity [3–5]. This involves advanced planning tools and algorithms to ensure efficient use of tracks and minimize potential conflicts. Several control systems, communicating with trackside equipment such as signals and switches. This communication is essential for coordinating the setting of routes and ensuring that the track layout aligns with operational requirements [6, 7]. Integration with train control systems is paramount, allowing for seamless coordination between the infrastructure and trains. The system continuously monitors train positions, adjusting routes in real-time to accommodate changes in schedules, unexpected delays, or other operational factors.

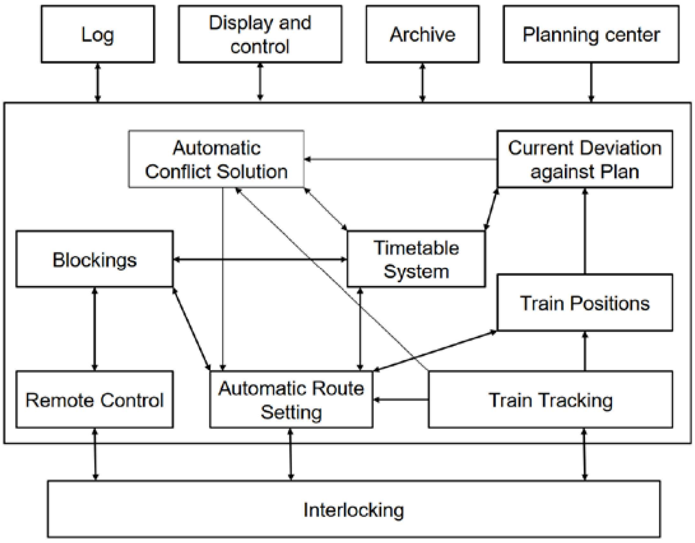

Figure 21.1 Overview exemplary architecture of a fully automated railway system [5]

Security measures are incorporated to prevent unauthorized access or tampering, emphasizing the importance of maintaining the integrity and safety of rail operations. Redundancy is also a key consideration, ensuring reliability by implementing backup mechanisms in case of system failures.
The ARS as one building block follows more of a rule-based approach in order to automate the setting of the track. This technology automates the process of determining and setting the optimal route for a train, considering factors such as the trains destination, schedule, and the current state of the rail network. The implementation of ARS plays a significant role in streamlining operations, reducing delays, and ensuring a more responsive and adaptive rail infrastructure [8]. It is a sophisticated technology integrated into rail signaling and control systems. Its primary objective is to automate the decision-making process related to route selection for trains, minimizing human intervention and optimizing the use of rail network resources [7]. However, the decision-making authority and responsibility still lies with the human being. This means that the ARS draws on existing information that is made available to the ARS and executes decisions automatically according to predefined rules. Accordingly, the ARS does not claim to be a safety-critical system, but rather to take over manual process sequences and thus relieve the signaler. The general principle is as follows. based on a timetable server, the points are triggered if the train position and timetable match. Otherwise, a warning or enquiry is communicated to the signaler via a human-machine interface (HMI) in order to resolve the conflict situation manually. The ARS can thus be embedded in the TMS as a supplement. This is intended to reduce the workload of the signaler. This process is therefore automated if no incidents or conflicts arise [9].

21.2.2. Criterias of Autonomous Systems

Planning tasks within the transport sector can be generalized across various domains and categorized into three levels [10]:

- Strategic level
- Operational level
- Control level

Strategic planning involves long-term tasks, such as network expansion and long-term timetable development. At the operational level, tasks are further divided into short-term planning and operations command [3]. In the rail sector, the control level is often referred to as the management or field level [3]. These tasks are not necessarily assigned to specific individuals but are instead associated with roles, allowing them to be distributed as needed.
At the operational level, key tasks include timetable creation, train composition, and infrastructure planning, with activities centered around disposition. These have a medium-term planning horizon. At the control level, tasks focus on train dispatching and the management of interlocking systems (both internal and external), which have a shorter planning horizon [3]. The core objective of the presented research result was to develop an innovative solution for the railway sector that aligns with the concept of autonomy, with route setting being a function that spans all levels mentioned.
Autonomy in the transport sector encompasses three key criteria [11, 12]:

1. Adaptability: The system is provided with a goal without detailed instructions on the process, allowing it to operate in changing environments with uncertain conditions. Autonomous systems are highly adaptable, modifying their behavior based on real-time data and learning from experience, unlike automatic systems that strictly follow predefined rules.
2. Independence: External intervention is not necessarily required, as autonomous systems are designed to function independently for extended periods with minimal human involvement. Automatic systems, by contrast, usually require regular oversight and intervention, particularly in unusual situations.
3. Decision-Making: Autonomous systems are capable of continuous learning and making decisions to achieve their objectives, even in unforeseen circumstances. In contrast, automatic systems are limited to executing predetermined instructions without the capacity for complex decision-making.

These criteria's highlight the key distinctions between automatic and autonomous systems, particularly in terms of independence, adaptability, and decision-making. Autonomous systems offer greater flexibility and reliability, raising important considerations around security, reliability, and trustworthiness. While both types involve automation, the level of human oversight and the system's ability to adapt and learn are the defining factors.

21.3. Autonomous Route Setting Architecture

To better understand and categorize the concept of autonomy, let's first explore the use case of anomaly detection in safety-critical infrastructure, such as server environments. Autonomous anomaly detection in these environments helps prevent hacker attacks by continuously monitoring and analyzing various data sources, including network traffic, system logs, application logs, and user behavior. The system begins by collecting this data to establish a baseline of normal activity through historical analysis. Once the baseline is defined, the system continuously monitors real-time data, comparing current activities against these established norms. Using statistical methods and machine learning algorithms, it detects any deviations from typical behavior. When an anomaly is identified, such as multiple failed login attempts or unusual network traffic patterns, the system flags the issue and alerts administrators [13–15].
In response to detected threats, the system can automatically implement risk mitigation measures, such as blocking suspicious IP addresses or isolating compromised servers to prevent further damage. The system also evolves over time by updating its models with new data and feedback, improving its ability to detect and respond to emerging threats. This proactive approach ensures that potential security threats are quickly identified and addressed, reducing the likelihood of successful cyberattacks [15].
In summary, the system operates without a precisely defined goal but learns to identify unwanted access attempts and makes decisions autonomously, without human intervention.
Several parallels can be drawn between the railroad domain and computer networks. Both involve systematically guiding and routing traffic, with critical nodes where reactive decisions must be made. In both contexts, there are established protocols for finding the optimal route to the destination, whether that be a server in a network or a station in a rail system.

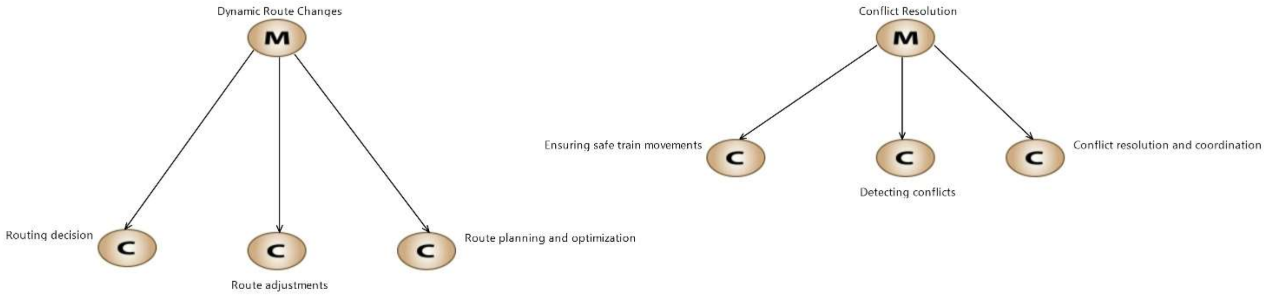

Figure 21.2 [MCB] AnRS Capabilities

The authors derived from these needs or aspects the following capabilities and missions that a route setting system should fulfill and defined the conditions for the AnRS. The authors made a system analysis, to describe the missions of Dynamic Route Changing and Conflict Resolution, identifying specific sub-capabilities that contribute to effective problem-solving. Dynamic Route Changing involves determining new routes (decision-making), adapting to changes, and permanently planning and optimizing routes under dynamic conditions. For Conflict Resolution, the key aspects include identifying conflicts, resolving them, coordinating actions, and ensuring safe train movements. During this analysis, it became evident that the distribution of tasks and the responsible actors can be distinctly separated between these two missions. Conflict Resolution primarily falls under the train dispatcher's responsibility, while Dynamic Route Changing is more within the train driver's domain.

The primary focus of the AnRS concept was ensuring that the system could seamlessly integrate with existing infrastructure and interlocking interfaces. This guarantees that the new system can be smoothly incorporated into current operations without causing disruptions. The concept also includes an operational analysis, which features scenario planning and a demonstration case study. This case study provides a practical example of the AnRS system in action, showcasing how the proposed solution functions in a real-world environment. The overall assumption is, that the decentralized AnRS system, trains and trackside equipment (such as switches and signals) communicate directly with each other to determine the best routes through a section of track. The system would operate on the basis of learned patterns that allow each component to make decisions based on real-time conditions.

Figure 2 shows a possible high-level integration of the AnRS into the existing traffic management infrastructure. The aim is to concentrate the decision-making processes and to place the AnRS as middleware between traffic management and interlocking for one specific coordination area. The coordination and cooperation on a macroscopic level will be realized as a distributed, decentralized system that enables greater flexibility and scalability. One challenge is to use the existing interfaces and continue to operate them unchanged. In doing so, the authors realize that two additional components are also required. An environment capturing unit and an information management system that ensures the correctness of the underlying database.

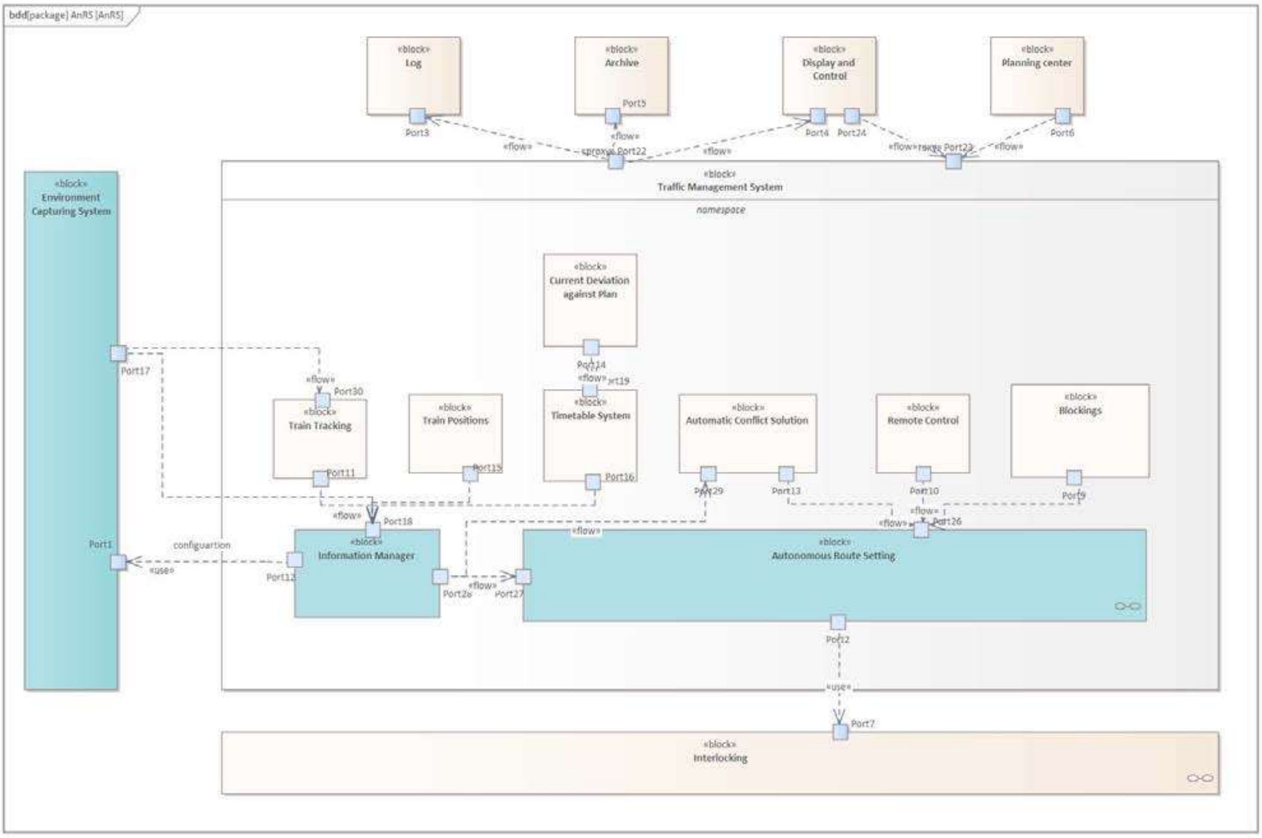

Figure 21.3 Draft overview about the AnRS integration into a fully automated railway system

Another challenge of this approach is in decentralized traffic management. In situations where no centralized control system along the line exists, each AnRS unit communicates directly with others at the edge, collaboratively establishing routes based on predefined Real Timetable Plan (RTTP) guidelines. This decentralized approach fosters agility and adaptability, allowing trains to navigate complex network configurations with ease. The integration of AnRS with RTTP also opens up opportunities for future advancements in rail transportation. By leveraging technologies such as artificial intelligence and machine learning, the system can continuously optimize routes, considering factors such as traffic patterns, weather conditions, and infrastructure capacity. This predictive capability not only improves efficiency but also enhances safety by proactively mitigating risks.

A significant advantage of the AnRS is its compatibility with existing infrastructure. By adhering to established interfaces and standards, the system can be seamlessly integrated into current setups, making it ideal for retrofitting projects—a point also considered in the concept. The integration of AI, as mentioned in the introduction, plays a crucial role in automate the decision-making within the AnRS approach. This technology enables the system to process real-time observation data, make adaptive decisions, and contribute to the overall efficiency and safety of railway operations.

21.4. Evaluation

The concept evaluation was conducted in two phases. First, the authors derived two use cases from accident reports to describe the AnRS function. Then, the authors present a setup on how the AnRS can be tested and integrated into the existing INDRA lab environment to demonstrate compatibility with current infrastructure.

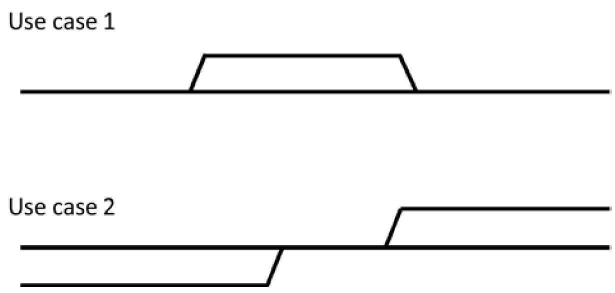

Figure 21.4 Track network of derived use cases for the concept evaluation

Use Case 1 – Passing Loop:
In a decentralized system, trains and trackside equipment communicate directly to determine optimal routes. For a single-track railway with passing loops, the system evaluates train positions and speeds to prevent collisions. It prioritizes the closest or most critical train and sets switches accordingly. If communication fails, the system defaults to a fail-safe mode, coordinating with other systems to maintain safety. This decentralized approach improves flexibility and efficiency, though reliable communication and rigorous testing are essential.

Use Case 2 – Rail Junctions:
At a rail junction where multiple tracks converge, a decentralized AnRS system manages train movements based on real-time data. The system prioritizes trains and sets switches to ensure safe passage. For complex scenarios, such as major interchanges with multiple levels, the system could coordinate both horizontal and vertical train movements. This decentralized control improves traffic flow and minimizes disruptions by optimizing decisions based on local and global cost functions.

Lab Demonstration
In figure 5 the planned demonstration and evaluation setup is designed. To show that the AnRS as a decentralized system could work, the authors planning to embed the system into a realistic simulation environment and connect it to the existing interfaces and show the approach based on the described use cases and scenarios. For the evaluation the authors have defined the following requirements to the simulation specially to perform verification and validation tasks to ensure the simulation accurately reflects real-world conditions and rigorously tests the system.

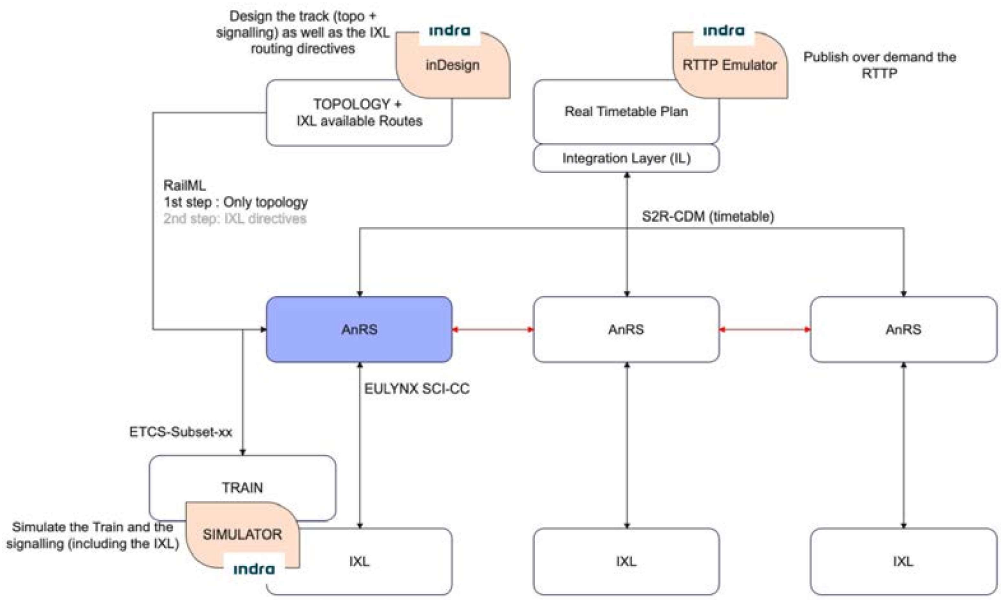

Figure 21.5 Planned Test setup for AnRS Concept - LAB Environment

21.5. Conclusion

The abstract presented the current results of the concept study for the AnRS approach. In comparison to ARS, which is a centralized system that automatically manages and controls railway routes based on predefined schedules and rules. The AnRS distributes the decision-making process across multiple autonomous nodes. Each AnRS system manages its local environment and cooperates with others to optimize routing. This system is adaptive and can dynamically adjust to changes like delays or track blockages without relying on a central command. ARS relies on pre-programmed logic to determine the best route for a train and typically requires human supervision to handle exceptions or unusual situations. Since ARS is centralized, a failure in the system can affect the entire network. In contrast, AnRS is more scalable and resilient to failures, and it operates with minimal human intervention, often using real-time data to make decisions. The future work focuses on the prototypical implementation of the AnRS approach and integrate the prototype into a realistic simulation environment.

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