# The importance of distributed intelligence traffic control systems in secondary railway transport


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*Abstract: One of the biggest challenges in modernizing secondary line rail transport is the high investment cost of safety and traffic control systems. The currently used centralized train control systems (e.g. Electra II., GSM-R) require significant infrastructure and maintenance costs, which are uneconomical on low-traffic, low-load railway lines. The research examines the applicability of a distributed intelligence, decentralized traffic control system. In this system each network element has its own processing unit and decision-making authority. It has modular structure and operates without a central computer, relying on the cooperation of autonomous devices. The RFID and LORA-based communication architecture enables real-time vehicle identification, monitoring of track element status, and local fault management. The economic advantage of the distributed intelligence structure is that it significantly reduces cabling, installation, and maintenance costs while increasing system reliability and scalability. The proposed solution offers a cost-effective and safe alternative to traditional centralized train control systems, especially for branch line railways, promoting the preservation of sustainable regional rail transport.*



*Keywords: Distributed intelligence, Decentralized railway control, LoRa communication, RFID-based train identification, Fail-safe systems, Secondary railway modernization.*

# 1 Introduction

Secondary rail transport plays a significant role in the transport network, especially in the case of low-traffic, regional lines. However, the cost of safety and traffic management systems, as well as the expected reliability and "fail-safe" operation, are particularly challenging in the modernisation of these lines. In order to improve the efficiency of side-line rail transport, it is therefore essential to adopt innovative technologies.

A conceptual framework for a 'distributed intelligence decentralised traffic management system' in which each network element possesses autonomous processing and decision-making capabilities and the network elements interact directly with one another. Conventional centralised traffic management and train control systems entail high investment and operational costs. [1] (largely due to extensive cabling, installation requirements, and maintenance demands.) On the other hand, it is worth exploring alternative cost-effective solutions for sidelines, which nevertheless guarantee high reliability and fail-safe operation. The essence of the decentralised distributed intelligence architecture is that the system is not built on a single central unit, but on intelligent subsystems embedded in trackside elements (e.g. switches, signals, rolling stock) that communicate with each other – e.g. vehicle identification, status monitoring, local error management. This structure reduces installation and maintenance costs – less cabling, fewer central units – while enhancing flexibility and scalability. [2] The use of a smart, decentralised architecture in rail transport has evolved from a theoretical concept into a viable engineering approach.

It should be emphasised that the aim of the 'distributed intelligence traffic control system' is not to fully replace the high-cost systems developed for high traffic main lines, but to provide a safe, reliable, cost-effective alternative for secondary line traffic. This approach can contribute to the preservation and revitalisation of regional rail transport, especially in areas where transport demand is lower and where traditional systems would be too uneconomical.

# 2 Core Concepts and Technical Foundations Distributed Intelligence and Decentralised Control

Understanding the technical foundations of the decentralised, distributed intelligence rail traffic management system is key for the application on secondary railway lines to be successful. ‘Distributed intelligence’ means that each element of the system, such as track section occupation sensors, switch controls, signalling controllers, vehicle identification units, is not merely actuators and sensors, but also possess own information processing and evaluation capacity and even decision-making powers. These decentralised units can communicate with each other in order to maximise traffic safety, train paths and track capacity, without the need for a centralised computer at regional or network-wide level [1]. Decentralised systems, made up of modular smart units, have already proved their worth in industrial control and, because of their scalability and flexibility, they are increasingly considered for use in railway applications. The decentralised structure allows decisions to be taken locally on the basis of current conditions, which means local real-time decision-making in traffic management. The principle of decentralised control reduces reliance on the central computer, thus increasing the reliability of the system.

It is of utmost importance that each decision point is redundant, meaning that there should be a backup control module, a separate communication path, and the system is designed to bring the system to a ‘safe state’ in the event of failure of any component. For example, a typical fail-safe mechanism ensures that loss of communication with othe system elemets triggers an automatic ‘stop’ command, halting the train or enforcing speed restrictions. In Hungarian: instead of a balanced state, it moves to a lower operational level, but there should be no unsupervised continuous movement. However, the failure of a system component is a clear demonstration of the inherent resilience of decentralised architectures, as if one module falls, the others can continue to function, so there will not be a complete system shutdown from a single error. [3]

When designing the system, design considerations must ensure that the components communicate according to uniform protocols, whether communication is wired or wireless. Functions such as vehicle identification, track occupancy detection, and status monitoring all rely on high-integrity data for which accuracy and latency are critical parameters. In addition, the system should be able to be integrated with the rail regulatory and safety standards currently in force: signalling systems, switches/points, automatic train protection (ATP), etc. Research indicates that such systems have the potential to reduce congestion and enhance safety, while system integration can be flexibly adapted to diverse railway infrastructures. [22] However, it must be emphasised that the decentralised architecture alone is not enough. The vulnerability and fault tolerance of the system components, including the underlying safety mechanisms, must also be properly designed. [4]

**RFID- and LORA-Based Communication Architecture Communication and Sensing**

By integrating technologies such as RFID for vehicle identification and LORA/LoRaWAN for wireless communication, these systems establish lightweight, long-range, and low-energy data links between trains, trackside equipment, and stations. LoRaWAN, in particular, supports the low-power, wide-area networking essential for cost-effective extension to remote and rural lines [5]. RFID tags on locomotives and rolling stock deliver continuous real-time location and identification data to the distributed control network. [5] LORA-enabled devices installed on trains and infrastructure elements (such as signals, switches, and track circuits) allow for bidirectional data communication about track status, maintenance requirements, and alarm conditions, even in locations with limited power and connectivity infrastructure. [5] In cases of GPS or GSM failures, LoRaWAN-based multi-hop localisation offers a robust fallback mechanism, reinforcing operational reliability on secondary or poorly connected lines. [6]

These probabilistic models have been mathematically and empirically validated on operational lines such as the Bologna-Vignola railway, proving the system's resilience to interference and environmental fluctuations, thereby assuring continuity of signaling functions under even adverse conditions. [6] In a domestic pilot project (MÁV Development Centre, 2024) the system measured the status of track elements and the position of trains via the LORA networks, resulting in significant cost and energy savings compared to conventional cable-based systems. The network was able to process incoming data locally and thus react rapidly to operational anomalies. As an international example, Swiss SBB operates a similar architecture, which significantly improved traffic flows and reduced the number of failures (SBB Annual Report, 2023).

However, RFID technology can fulfil multiple functions in the railway environment: it is primarily employed for vehicle identification, but it can also support track element identification (e.g. switch module identifier). RFID devices may be connected to railway equipment or trackside objects and thus integrated into a real-time tracking system. [7]

LORA technology (Long Range) can be a positive choice for secondary lines, as it offers a long communication range and low energy consumption and requires only modest infrastructure. For example, trackside control-and-detection modules can function as LORA nodes that communicate with each other and with the central or regional surveillance system as required. This enables the collection and transmission of status data (track occupancy, switch positions, and module indicators) and distributed decision-making across the system elements.

**Economic and Operational Advantages Cost Savings**

The introduction of a decentralised distributed intelligence system is not merely a technical issue – its economic and operational benefits are also significant, especially in the context of secondary-line rail transport. Distributed intelligence minimises the need for expensive and failure-prone central cabling networks, extensive signal control rooms, and dedicated communication backbones. [1] In such systems, much of the intelligence as well as failure detection and basic recovery actions are moved to the edge, where they can be handled by modular, replaceable devices [5]. Implementation on secondary lines has demonstrated significant reductions in up-front installation and ongoing maintenance costs, largely due to:

- Reduced length and complexity of cabling needed
- Reduced power-infrastructure investment for network backbone equipment
- Simplified and scalable maintenance, as individual components can be upgraded or replaced without affecting the whole system [5]

It is estimated in practice that a reduction of up to 30 % to 50 % of the cost of cabling, the construction of a central control station, licences and long-term maintenance charges on a sideline could be achieved. In addition, easier extensions make the installation of future developments significantly more cost-efficient (e.g. new sensors, automation).

The advantage of a decentralised system is also operational flexibility: as each section acts as a smart module, the maintenance or modification of that section can be partially done independently. For example, if a section of line is closed for maintenance purposes, the other sections can continue to operate – the entire line is not forced into shutdown due to the failure of the central system. In addition, the system can be easily expanded: the addition of new sensors, communication modules does not require a new central control station or large-scale infrastructure – it can simply be installed as a new section-level control module. [8]

# 3 Reliability and Scalability

Distributed systems inherently provide higher reliability and resilience against local failures: one processing node or segment suffers a fault, its adjacent nodes can often compensate or re-route trains as needed, without catastrophic system downtime [9]. This node autonomy also means that the system is more readily scalable – new secondary lines or connection points can be added by simply integrating additional smart modules, without redesigning the entire network's logic. [22]

Secondary lines are characterised by low turnover and a slower return on investment. This means that only technologies that are cost-effective and easy to operate can be considered. The decentralised system is well suited to this, because each section is operational on its own and does not need to be built on large central facilities. Thus, the owner or operator of the line can install a safety solution at a lower risk. In addition, if modules can be installed in a modular manner, e.g. in a subscription model ('sensor module monthly fee'), the initial investment may be lower. This may be particularly important in regional or municipally owned railway lines.

Modernising rail transport is no longer just about traffic management and safety, but increasingly about automation and energy efficiency. Automation can be interpreted at several levels: vehicle control (e.g. automatic driving, GoA), traffic control, maintenance automation. The decentralised architecture fits well, as local modules are able to make automatic decisions, e.g. speed reduction, state control, error response, without always requiring central decisions. [13]

Reducing energy use is an important aspect – especially when the line has low traffic and revenues are limited. A decentralised system supports energy efficiency by using smart controls – such as signals, lighting and switch settings only when necessary; sensors enter sleep mode, communication is optimised (e.g. less frequent data transmission). In addition, smart system components supporting local decision-making lead to less data being transferred to the centre, requires less grid energy and results in lower latency. [2] Automation should not only cover train movements – it also has great potential at system monitoring and maintenance level. Smart sensors support predictive maintenance through continuous state monitoring: if an anomaly is indicated by a track element (e.g. an abnormal control state), the local module gives an immediate signal and may even take a mitigation step (e.g. imposing a restriction or holding the train). [14]

Studies of modular distributed-interlocking systems for railway stations have shown that logical unit partitioning and minimised communication overheads are essential for ensuring traffic safety and optimising throughput [18]. Real-world pilot implementations and mathematical models evaluating LoRaWAN-based railway signalling on secondary lines have validated this technology stack's ability to maintain high reliability for vehicle identification and track state management, even under interference and challenging environmental conditions

[6]. Automation and modular intelligence are also aligned with broader trends in transport digitalisation and the shift towards “smart” railway operations, aimed at improving safety and reducing costs across passenger and freight segments – without sacrificing operational flexibility [10].

# 4 Interfacing with Renewable Energy and IoT Integration

Decentralised and smart railway control aligns well with the trend of integrating IoT and renewable energy solutions for broader railway infrastructure, supporting not only digitalised signaling but also more energy-autonomous operation and resilience against network-wide failures [11]. Distributed edge devices in railway signaling systems increasingly incorporate IoT protocols and edge computing, enabling local data fusion and real-time analytics without heavy reliance on cloud resources or central computer resources [12].

The core of the IoT is the systematic connection of sensors, controllers and network devices, with data collection and real-time communication. In rail transport, this takes the form of infrastructure monitoring (e.g. track section occupation, switches, temperature, vibration), rolling stock identification (RFID) and train tracking. [4]

Edge computing means that data processing takes place close to the device or location where the data is generated – not all data needs to be sent to the cloud or to a central server. This reduces latency, grid load and increases the robustness of the system. [2] [15]

Data security, encryption of communications, device identification and system protection against cyber-attacks are particularly important for IoT and edge architectures. (DoS attacks and risk of misuse of data). [4] Furthermore, the decentralised architecture helps to avoid a single point of failure – the system components continue to function, even if the central communication is interrupted.

Smart monitoring and security support are one of the most advanced layers of a distributed intelligence system. In this chapter, I look at how AI technologies (machine learning, image processing, anomaly detection) can be used on railway secondary lines with practical examples and references.

AI (machine learning, deep learning) can recognise patterns that are not traditional rules-based systems. For example, detection of foreign objects on the track: the 'Intelligent Railway Foreign Object Detection: The Semi-supervised Convolutional Autoencoder Based Method' shows how convolutional autoencoders are used to detect unauthorised objects on the track without the need to know predefined categories. [16]

Railway infrastructure is increasingly equipped with sensors: rail condition, vibration, temperature, position of switch mechanism. Algorithms running on Edge-AI platforms (e.g. FPGA-based systems) can indicate errors in real time (up to 88.9% of faulty rails can be identified). [17] Thus, in the sideline system, the modules not only communicate and control but also continuously monitor the conditions and predict errors or anomalies with AI algorithms. For example, modules can recognise if the switch position has changed or the engine current has risen persistently – and trigger pre-warning maintenance. AI algorithms allow local modules to automatically determine safe conditions and switch to error handling mode when needed.

**Advanced Wireless Control and Self-Triggering Mechanisms**

The following levels of intelligent distributed systems involve the use of wireless control and self-management mechanisms: automation functions that autonomously change mode, prevent errors or react to faults based on device conditions or ambient conditions. A self-management mechanism implies that the device detects its own state, such as a rise in motor current, an increase in rail vibration, an incorrect contact-position signal, and independently initiates the next step: e.g. imposing a speed limit, holding the train, or automatic migration to a secure mode. [14] The security protocol is a critical issue for such automated functions: self-management should always be deterministic – i.e. detection, decision-making and implementation must be reliable and fully documented. The system must have an event log and be auditable, in particular with regard to railway licensing requirements. Moreover, the reliability of communication channels (radio links), redundancy, interference protection and physical protection of assets (e.g. vandal-resistant enclosures) are important.

## Conclusions

Distributed-intelligence, decentralised control using RFID and LORA architectures provides a practical, cost-effective, and robust solution for secondary-line railway modernisation, especially in low-traffic or resource-constrained environments. These systems demonstrably reduce investment and operational costs, improve fault resilience, and offer scalable, future-proof infrastructure for evolving transport demands. [6] [18] [5] [9] [10] [11] [12] [19] [20] [21] It is important to highlight that in practical implementation, not only the technology, but also engineering design, operational strategy, redundancy structure and certification process are important. The decentralised architecture allows each network component to have its own intelligence, thus reducing dependence on the central controller, increasing system redundancy and reducing the risk of single-point failure. The RFID and LORA-based communication architecture is well-applied in a secondary-line environment: low-cost, easy to install and operate while allowing vehicle identification, track element monitoring and local decision-making. Lower infrastructure costs, scalability, operational flexibility, and increased availability all contribute to a more sustainable secondary rail network. IoT and edge computing architectures enable the implementation of a network of sensors and modules, with real-time data, local decisions and rapid response, while AI-enabled monitoring and self-triggering mechanisms ensure that the system does not merely follow conditions passively, but also actively responds to technical failures and security incidents.

The harmonisation of railway safety and communication standards and the use of new wireless communication technologies (5G/FRMCS) may be necessary in order for such decentralised systems to be widely deployed. It is important to highlight that predictive maintenance and optimal traffic management with AI algorithms further increase economic sustainability. However, where IoT devices and network modules are increasingly used, the risk of cyber-attacks also grows, and appropriate protection mechanisms are needed.

## Authors' Declaration

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