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# RAIL VEHICLE LOCATION IN THE CONTEXT OF IMPROVING THE EFFICIENCY OF RAILWAY INFRASTRUCTURE USE – AREAS OF GNSS APPLICATION

**Michał STEUER[1, 2], Rafał BURDZIK[3], Andrzej KOCHAN[4]**

[1] *Doctoral School, Silesian University of Technology, Katowice, Poland*

[2] *Egis Poland Sp. z o.o., Warsaw/Katowice, Poland*

[3] *Faculty of Transport and Aviation Engineering, Silesian University of Technology, Katowice, Poland*

[4] *Faculty of Transport, Warsaw University of Technology, Warsaw, Poland*

## *Abstract:*

*Modern rail transport requires precise traffic management to ensure safety and operational efficiency, which is only possible when the Control-Command and Signalling (CCS) system relies on accurate, real-time information about the location of rail vehicles within its area of influence. Precise positioning is essential for maintaining safety levels, optimizing traffic flow, and ensuring the smooth functioning of the railway network. Global Navigation Satellite Systems (GNSS) enable continuous monitoring of train positions, creating opportunities to improve infrastructure efficiency and traffic management by supporting more flexible control strategies, better use of existing capacity, and the introduction of advanced automation. However, implementing GNSS in CCS systems presents challenges related to the absence of defined evaluation criteria, system architecture, and verified levels of accuracy and availability required in rail operations. These issues highlight the need for developing guidelines and technical and formal assumptions that define and characterize the potential application area of GNSS in CCS, helping to determine operational boundaries, constraints, and compliance with railway standards. This publication outlines a process designed to answer the fundamental question of: is it possible to use satellite systems in railways, and if so, to what extent? The implementation of this process begins with an analysis of the current state of knowledge and technology, including requirements and guidelines for the use of satellite systems in railway applications and their role in automatic train operation within the European Rail Traffic Management System / Automatic Train Operation (ERTMS/ATO). It then incorporates research and simulations assessing the availability and accuracy of satellite positioning under various operational conditions, providing insight into the performance of GNSS in the railway environment. The process concludes with the identification of potential areas of implementation and directions for further research, creating a coherent basis for assessing the feasibility and scope of GNSS use in railway traffic control and management systems.*

***Keywords:*** *GNSS, ERTMS/ATO, train rout setting, efficiency*

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**Contact:**
1) michal.steuer@polsl.pl [https://orcid.org/0009-0004-2360-2298] - corresponding author; 2) rafal.burdzik@polsl.pl [https://orcid.org/0000-0003-0360-8559]; 3) andrzej.kochan@pw.edu.edu [https://orcid.org/0000-0002-8183-8926]

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## 1. Introduction

The performance and quality of modern train control systems depend mainly on the devices and positioning systems used. The basic functions of such solutions are to determine the absolute position of a train, including parameters relevant to safety, such as accuracy and reliability, speed, acceleration, and the allocation of track-side and on-board resources. The result of determining the location of a given rail vehicle is used for the purposes of the railway traffic control and management system, based on which railway traffic is conducted in a manner that prevents collisions and optimizes the use of infrastructure, which has a significant impact on the safety and capacity of railway lines. The above criteria for the positioning function can potentially be met by using GNSS functionality. The general assumptions for GNSS refer to the possibility of extracting records from GNSS positions and then using the data for analysis to determine the position of a rail vehicle in the railway infrastructure. This is achieved by extracting features in the form of spatial and temporal information, such as speed, acceleration, direction, and distance for each vehicle individually or collectively for all vehicles in the location area. The extracted features can be used as input data for Control-Command and Signalling systems to define a dynamic graph of railway traffic in the area under study (Sadeghian, Håkansson, & Zhao, 2021) (Chrzan, Kornaszewski, & Pniewski, 2021) (Kochan, 2022) (Lewiński, Perzyński, & Toruń, 2016).

## 2. Literature review

Global navigation satellite systems have undergone rapid evolution in recent years, driven by advancements across major constellations such as GPS, GLONASS, Galileo, BeiDou, and QZSS (Severi, et al., 2018). Their growing precision and reliability have strengthened their role in transportation sectors, especially in rail applications where accurate localization is crucial for safety and efficiency (Marais, Meurie, Attia, Ruichek, & Flancquart, 2014).

Mobility data derived from GNSS tracking has increasingly supported traffic analysis, safety assessments, and transport infrastructure planning (Krasuski, 2019). Within the railway domain, precise detection of train position is fundamental for maintaining line capacity and preventing conflicts in traffic flows. Research highlights that GNSS-supported positioning when complemented by digital maps or sensor fusion can improve detection accuracy and support future signaling concepts (Diani, Sbardellati, & Lisi, 2019). A systematic review of the literature indicates a steady increase in scientific interest related to GNSS-based applications in rail systems over the past two decades (Liu & Hu, 2012). From an initial corpus of nearly two thousand articles, only a selected portion directly addresses challenges associated with GNSS reliability, signal availability, and suitability for safety-critical rail operations. These studies consistently emphasize the importance of formulating robust system architectures that support satellite-based positioning under diverse operational conditions (Severi, et al., 2018) (Mikhaylov, et al., 2023) (Wang, et al., 2022) (Cai, Liu, Dong, & Liu, 2023).

Despite continuous improvements in GNSS constellations, fully reliable railway-grade positioning typically requires integration with complementary measurement sources such as inertial sensors, odometers, or digital maps (Marais, Meurie, Attia, Ruichek, & Flancquart, 2014). Further development of satellite systems and updated technical documentation help expand the potential for implementing location-based solutions in rail transport, reinforcing the foundation for future research and deployment (Liu & Hu, 2012).

## 3. Research problems

### 3.1. Satellite positioning in the context of CCS systems

The use of satellite systems in rail transport has been discussed for many years. As presented in (Steuer, Burdzik, & Piednoir, 2025) , the first projects and studies related to the assessment of the possibilities of using satellite systems in rail infrastructure took place before 2000 and are still being implemented today. The research projects include: APOLO, GADEROS, LOCOPROL, GaLoROI, 3inSat, NGTC, Shift2Rail (currently continued under the name Europe's Rail Joint Undertaking) and RTGMS. The latter two are ongoing projects, and RTGMS is being implemented in Poland by the National Research Institute of Telecommunications in cooperation with the Main Office of Geodesy and Cartography. The strategic use of satellite positioning systems in railways is also being discussed throughout the European Union (EU), as evidenced, among other things, by the conference entitled *"Space for Innovation in Rail"* organized in Madrid in 2023. Despite numerous projects and ongoing discussion on the subject, it is futile to look for examples of GNSS implementation in railway traffic management, let alone control. The problem mainly concerns the European market, where an extensive railway network is an important branch of the transport industry, and its operating results have a significant impact on the overall condition of transport in Europe.

This raises the question of what is slowing down the implementation of GNSS in rail traffic control. Could the reason be insufficient funding for this purpose? As numerous EU-funded research projects show, this is unlikely to be the obstacle. Could the reason be limited access to satellite systems? Such a risk is, of course, likely, but with the implementation of the European program to build the Galileo Global Navigation Satellite System, which is the only one independent of military institutions and is managed, among others, by the private sector, such a risk, especially for EU member states, should not be a basis for excluding GNSS in rail transport. According to the report (European GNSS Service Center, 2025) for the first quarter of 2025 *by the European Union Agency for the Space Program* (*EUSPA*), the Galileo system has achieved full functionality and exceeded the required performance thresholds. Could the reason be insufficient positioning accuracy using satellite systems? The ubiquity and functionality of these systems is demonstrated by their commercial use in many industries, including applications requiring high precision, such as geodetic measurements, where the required accuracy is measured in centimeters. Of course, the conditions for using GNSS in static measurements are significantly different from those for positioning a moving object. This issue is discussed further in this publication in the section on positioning research (Chapter 3). Could the reason be rail transport itself, whose infrastructure is characterized by numerous elements that may limit or even prevent the use of satellite positioning (tunnels, viaducts, bridges, traction network, location in the field, etc.)? Adding to this the lack of formalized assumptions regarding the area of GNSS use in rail transport and the logic of the currently used signalling systems, it is necessary to precisely target the possibilities of using satellite positioning for rail vehicles and their expected functionality so that the pace of potential implementation reflects the commitment to project implementation, financing, and discussions conducted at various levels and in various environments (academic, governmental, EU, etc.).

Moving on to defining the area of GNSS use in rail transport, the first step is to assess the possibility of using satellite positioning as a separate system or as an integral part of other subsystems currently in use or in the future. In this consideration, we are faced with a situation which, for the purposes of guiding further action, requires the identification and analysis of the limitations resulting from the architecture and operating logic of individual subsystems. The term "subsystems" is understood to mean:

1. IXL (*Interlocking System)* – a dependency system (which may be computer-based) responsible for controlling rail traffic, whose functionality ensures the safety of train movements by preventing collisions. It implements dependencies between track devices such as point machines and semaphores. It operates at the operator, dependency, and setting levels.
2. ETCS - *European Train Control System*, part of ERTMS. It provides digital control of train operation. ETCS replaces or supplements traditional trackside signalling with cab devices and enables automatic supervision of train operation, including emergency braking in case of danger.
3. ATO is an automatic train operation system that works with ETCS. It enables train operation at various levels of automation, known as *Grades of Automation* (GoA), from advisory mode for the driver (GoA1) to fully unmanned operation (GoA4). The ATO system helps optimize driving in terms of punctuality, energy savings, and passenger comfort.
4. TMS is a *Traffic Management System* that supports dispatchers and operators in planning, coordinating, and optimizing train movements. The TMS analyzes traffic, infrastructure, and timetable data to dynamically manage train flows, minimize delays, and increase network capacity.

The above characteristics of the systems allow specific functionalities and responsibilities to be assigned to the systems, creating a dependency matrix presented in Table 1.

Table 1. Matrix of dependencies and system functionalities

| **System** | **Safety** | **Traffic control** | **Traffic control** | **Interoperability** | **Interdependence*** |
|---|---|---|---|---|---|
| IXL | P | O | P | O | - |
| ETCS | P | O | P | P | IXL |
| ATO | O | P | O | P | ETCS |
| TMS | O | P | O | P | ATO |

*The interdependence in the table above determines the dependence of a given system on data obtained through or from another system installed in each railway infrastructure.

For each of the above-mentioned subsystems, vehicle location information is crucial due to the specific functionalities of these subsystems. This means that information from the GNSS system should be available and addressed with appropriate levels of security in communication between systems. Sharing data outside the systems requires the use of an additional communication port, which in the context of cybersecurity may be a potential threat to the integrity of security levels. Therefore, obtaining information from security systems for the purposes of traffic management in railway infrastructure poses a certain difficulty and risk to the safety of railway traffic. Therefore, considering the benefits and potential difficulties and risks, the use of GNSS systems should be characterized by a high level of security in the sharing of data for the purposes and functionality required, thus creating a subsystem that provides data at the expected level of confidence and accuracy, taking into account the required levels of data transmission security.

### 3.2. Areas of application of satellite systems in railway infrastructure

Considering the above assumptions, in order to illustrate the area of application of GNSS in railways, for further consideration, a theoretical separation of the GNSS system is assumed, ensuring the best possible use of its functionality. As presented in (Tonk, Boussif, & El-Koursi, 2025) , data for the TMS subsystem is obtained directly from the signalling subsystems. According to the above analysis, this approach poses a potential threat to the functioning of systems responsible for the safety of railway traffic. To minimize or completely exclude communication between the systems in question, some of which are responsible for operational considerations and others for the safe operation of rail traffic, the functional separation of the GNSS subsystem allows for the free transfer of data without the need to create intersystem communication paths. Such separation could form the basis of categorized data, made available depending on the expectations of the related system. This approach would result in a process structure as shown in Figure 1.

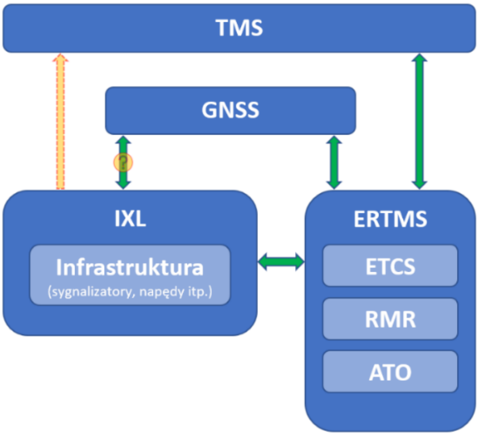


Fig. 1. Process structure with GNSS subsystem implementation (source: Author's own work)

The structure presented at this stage indicates that communication is characterized by data exchange at the "everyone with everyone" level. This approach may seem justified to minimize the risk of communication loss at any level, but as shown above, it is a solution that may pose potential risks to subsystems responsible for railway traffic safety. Following this direction, the communication path indicated in orange may be excluded or significantly limited. Furthermore, the communication path between IXL and GNSS, indicated by the question mark "?" may be excluded or similarly limited in its functionality to increase the security of the entire CCS system.

Maintaining the assumption of functional separation of the GNSS system, the next step is to define the communication hierarchy between systems. According to Figure 1 and the assumptions described above, the main communication path includes TMS↔ERTMS. The basic exchange of data between the subsystems in question is intended, among other things, to illustrate the traffic situation within the TMS coverage area. Knowledge of the current load on the railway infrastructure, temporary or delayed train connections, and the exact locations of individual vehicles is a key aspect of proper and effective management using the traffic control system. As proposed in (Tonk, Boussif, & El-Koursi, 2025) , railway traffic management is characterized by a hierarchical structure as shown in Figure 2.

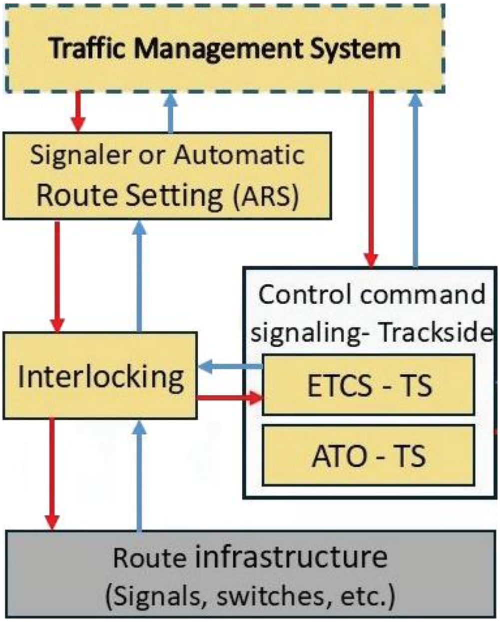


Fig. 2. Hierarchical structure for the TMS management system (source: Tonk, Boussif, & El-Koursi, 2025)

This hierarchy indicates the need for data exchange between individual modules, but, as before, it does not consider the physical separation of the module responsible for data exchange. This is due to the lack of defined guidelines specifying the method of communication and the tool responsible for this process. Industry discussions on this topic are currently underway, and research projects are being carried out, including as part of Europe's Rail Joint Undertaking program.

Following similar considerations regarding the need to create a separate subsystem, it is proposed to include the GNSS system as a functionally separate subsystem responsible for transmitting data on the positions of individual rail vehicles. Considering the above and the hierarchical structure of TMS management, the TMS↔ERTMS process structure is presented in Figure 3. Since this publication does not consider the issue of *Automatic Route Setting* (*ARS*), it has not been included in the figure below, and the *Radio Block Center* (RBC) represents the central unit of the ETCS system responsible for sending the appropriate messages and commands to the on-board system (Steuer M. K., 2023).

As can be seen in Figure 3, direct communication between the GNSS system and ERTMS takes place in the GNSS↔ETCS relationship. This is since the positioning of a given object, in this case a rail vehicle, is determined from the level of that vehicle. A given train determines its position using a GNSS signal, then processes the information and relates it to the digital railway infrastructure area, and subsequently transmits information about its location to the RBC central unit, which calculates and determines the assumptions for further driving parameters of the train on this basis. The above process is identical to the principle of operation of the ETCS Level 2 system, where an on-board unit called an odometer is responsible for determining the location of a rail vehicle.

The above graphic also shows other communication processes. The first of these involves RBC→TMS communication. The transfer of information from RBC to TMS seems justified due to the characteristic data that can be used for the purposes of railway traffic management in each area. For this scope, work is underway on the technical specification of the so-called Subset-131, which has not yet been approved as part of the *European Union Agency for Railways* (ERA) specification set. Figure 3 also shows the GNSS→TMS and GNSS→ATO processes. These processes can be used to transfer information that is not defined as critical from the point of view of railway traffic safety, but only supports railway traffic control processes.

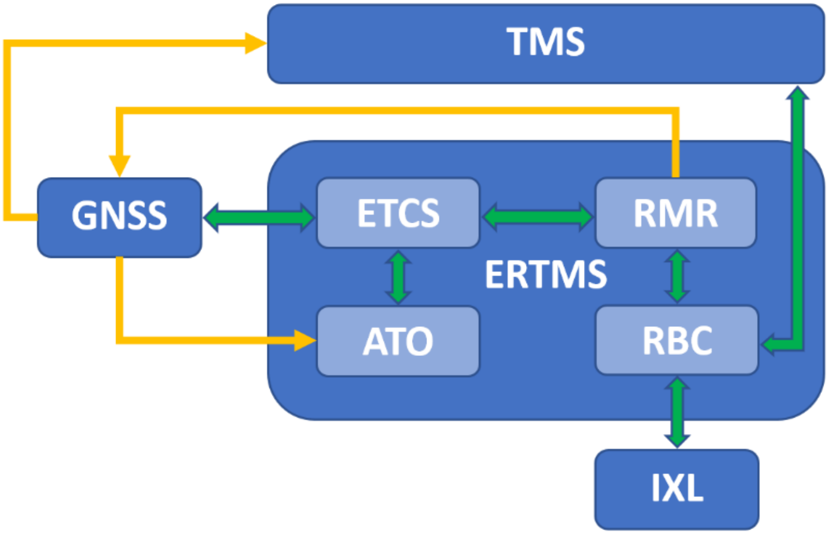


Fig. 3. Process structure diagram (source: Author's own work)

Considering the process of creating a process structure described in this chapter, as well as the characteristics of CCS systems, it seems reasonable to assign the GNSS subsystem as an integral part of the ERTMS subsystem. Despite the functional separation of GNSS described in this chapter, the above is intended to guide the implementation of satellite systems as part of the expansion of the functionality of systems currently being developed and implemented within the railway infrastructure. Taking into account the process of creating a CCS system structure based on GNSS functionality, the process structure diagram would look as shown in Figure 4.

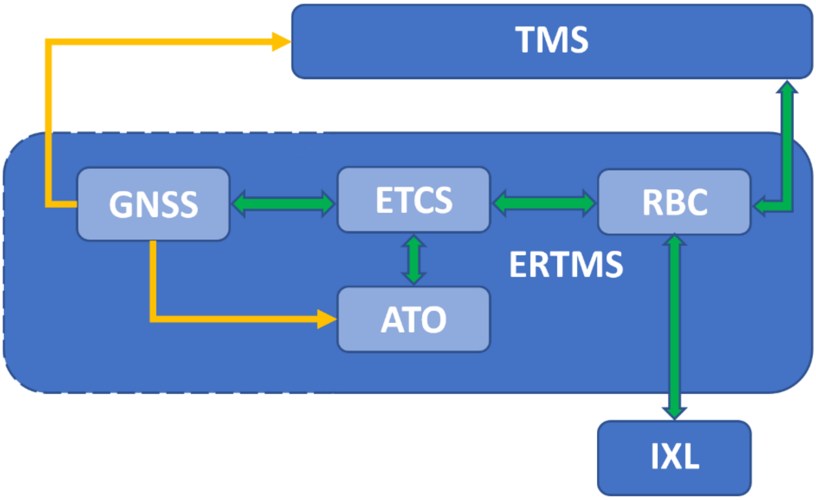


Fig. 4. Process structure diagram with an integrated GNSS subsystem within ERTMS (source: Author's own work)

The presented process structure, in which satellite systems are included within ERTMS, requires the development of guidelines and normative specifications defining the assumptions for the implementation of Global Satellite Systems for Railways within the European Rail Traffic Management System, known as ERTMS/GNSS-R (*ERTMS GNSS for Rail*). Furthermore, by distinguishing between the levels of GNSS-R use in railways, it is possible to introduce the concept of grades of satellite system implementation in railways, known as GoGNSS-R (*Grades of GNSS-R*).

### 3.3. GNSS system architecture

The process structure presented in the above chapter, in which GNSS constitutes a satellite positioning subsystem for rail vehicles, requires the definition of a GNSS system architecture that ensures continuous and rapid data exchange, enabling the tracking and mapping of a given train's location in real time.

#### 3.3.1. Inertial systems

One possible solution is to use Global Navigation Satellite Systems with GNSS/INS *Inertial Navigation Systems*, as presented in (Marais, Beugin, & Berbineau, A Survey of GNSS-Based Research and Developments for the European Railway Signaling, 2017) . This architecture is based on the integration of multiple sensors to avoid the risks associated with potential GNSS errors, including unavailable or limited satellite signals, multipath effects, and others. The use of inertial sensors in the differential satellite positioning process can provide accuracy of approximately one meter, which can contribute to more effective determination of train position, speed, and other required state descriptions. A simplified GNSS/INS architecture is shown in Figure 5, where OBC stands for on-board computer and IMU is an inertial measurement unit.

Correlation of data from individual sensors allows for a more comprehensive range of rail vehicle location on railway infrastructure. The data detected by the sensor will enable the creation of a dynamic path of movement of a rail vehicle equipped with an inertial system, which translates into high positioning accuracy and train trajectory. Thanks to the ability to determine the position of the vehicle using an inertial system and then visualize this location based on a precise map of the railway infrastructure, it is easier to visualize the traffic situation in the area covered by the system to ensure railway traffic safety and optimize the transport process.

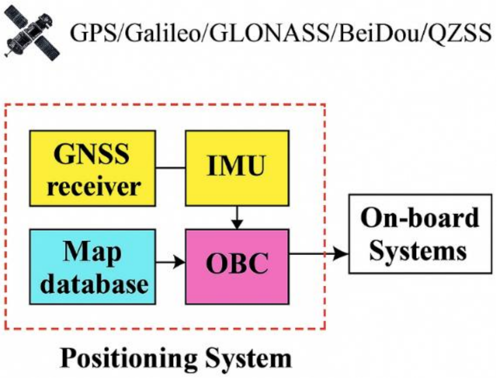


Fig. 5. Simplified GNSS/INS architecture (source: Author's own work)

#### 3.3.2. GNSS multitracking

The term "multitracking" in railways is associated with the use of several parallel tracks on a single line, which increases capacity and allows trains to run in both directions simultaneously. However, for the current scope of this publication, the term is used to refer to a GNSS positioning system in which the object being located is equipped with more than one tracker module. This solution is increasingly used in areas such as geodesy, robotics, aviation, and others. (Bures, J., Vystavel, O., Bartoněk, D., Barta, L., , 2024) The use of multiple trackers to track the location of a given object is justified in the context of:

- **increased accuracy** - the deployment of several receivers allows for the elimination of measurement errors and the acquisition of more precise positional data,
- **determining *heading*** – thanks to multiple reference points, the system can determine not only the position but also the direction in which the object is moving,
- **redundancy and reliability** – the failure of one receiver does not prevent the system from continuing to operate.

The above-mentioned characteristics of multitracking systems may also argue in favor of their use in railways. In addition, the use of at least two locators on a single train allows such a system to be used to determine whether the train is moving along a given section or has become uncoupled. This solution may be equivalent to or complement the requirements for the on-board *Train Integrity Monitoring System* (TIMS), whose functionality and scope of application are characterized by the *Technical Specifications for Interoperability* of the *Control-Command and Signaling* Subsystem (TSI CCS). Figure 6 shows a simplified representation of the use of a GNSS multitracking system installed on a train.

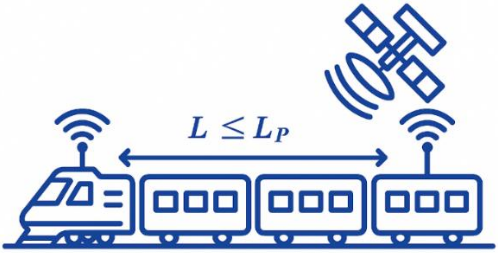


Fig. 6. Train equipped with a GNSS multitracking system (source: Author's own work)

In Figure 6, "L" represents the distance between the locators installed on the train, as defined in the system, while "$L_P$" represents the length of the train equipped with the system. The use of the "≤" sign results from the fact that the algorithm for calculating the distance between two locators will always interpret the section between them as a straight line, which, due to the characteristic curves during railway lines, means that the length of this section will not be constant. In addition, defining the smallest possible distance between locators, which is a result of the characteristics of the railway line on which a given train is traveling, can provide additional functionality whereby the system interprets the exceeding of the smallest possible distance "L" as an event in the form of a collision or derailment of a train.

### 3.4. Rail vehicle location and train route setting

According to what is presented at (Asuka & Komaya, 1997) (Yuan & Hansen, 2004) (Haramina, Širol, & Sumpor, 2020) , the process of setting the route begins with checking the availability of tracks and traffic control devices. The dispatcher sets the switches to the appropriate positions, blocks the route for other trains, and activates the signal allowing the train to proceed. This process is the same for conventional railway traffic control devices and computerized ones, where route setting is performed using a computer console. Once the route has been set, all tracks and devices included in it are considered occupied, even if the train has not yet arrived. This means that no other route that would conflict with the already reserved route can be set. This block remains in place until the train has completed its entire journey and the system automatically releases the route. The occupancy of tracks resulting from the set route has a direct impact on the capacity of the station. The dispatcher must decide which routes to set first, considering, among other things, train delays, their priority (e.g., passenger or freight), and track availability. Improper management of routes can lead to congestion and delays.

In the publication (Yuan & Hansen, 2004) , the authors present an analytical approach to a case study related to The Hague HS station, which plays a key role in the railway system as an intersection of many regional and long-distance lines. Due to the complex track structure and limited number of platforms, the station's capacity is strongly dependent on how train routs are set. The authors analyze how different routing scenarios, especially those involving crossings and changes of direction, can lead to traffic conflicts and delays. The complexity of the routes at The Hague HS station is shown in Figure 7.

In the capacity analysis of The Hague HS station, taking into account the pre-setting of the route significantly increases the estimated value of infrastructure occupancy compared to an analysis based solely on the actual track blocking time. The largest increase was recorded for track 5, at 34.8%, which shows how strongly advance route reservation affects resource availability. Taking this factor into account allows for a better reflection of actual operational constraints and potential route conflicts between trains. Considering the above, it has been shown that optimizing route setting significantly improves traffic flow efficiency.

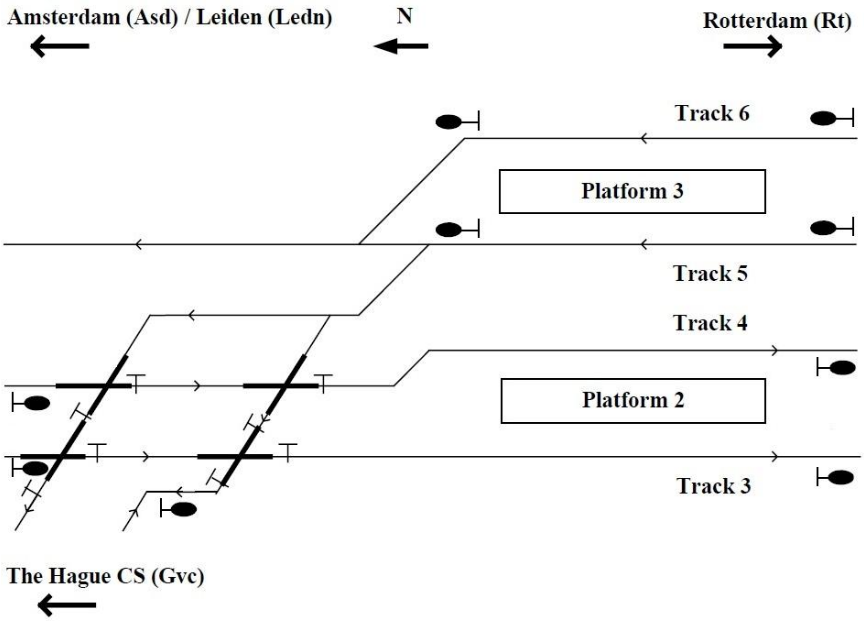


Fig. 7. The turnout head of The Hague HS station (source: Yuan & Hansen, 2004)

Analyzing the above case study and assuming the goal of the most efficient use of railway infrastructure, it is necessary to carry out the route setting process as late as possible before the approaching train reaches a given setting district to minimize the time of track occupancy and the devices securing that route. This is only possible if the location of the approaching rail vehicle is precisely known to the traffic controller in charge of the given signaling district. A potential improvement in the implementation of the above process could be the implementation of a GNSS system to inform the traffic controller of the exact location of the approaching train or the complete automation of this process using the aforementioned ARS. The relationship between the time required to set the route and the impact on the capacity of a given railway junction is shown in Figure 8.

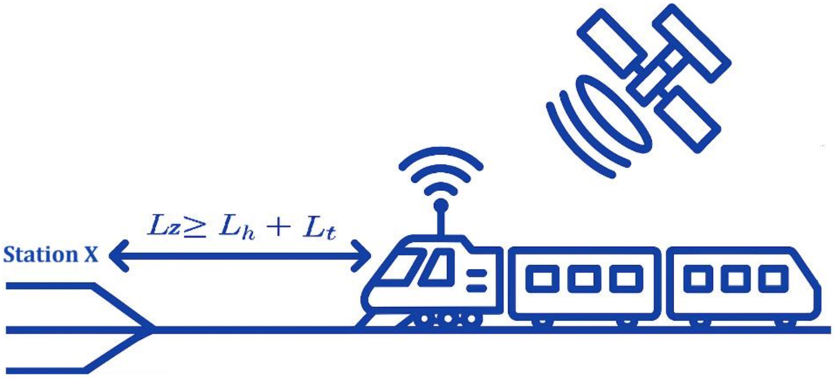


Fig. 8. Location of a rail vehicle in relation to route setting (source: Author's own work)

The relationship between the required minimum distance (approach distance) "$L_z$" of a rail vehicle from the point where the route at station X should be set is the result of the braking distance "$L_h$ " and the distance "$L_t$ " resulting from the time necessary to set the route, the response time of the dispatcher, and other time factors ensuring a safe and optimal time for this process. The lower the value of "$L_t$ ", the shorter the occupancy time of the tracks and devices covered by the route, which in turn translates into the optimization of the use of the infrastructure of a given station.

### 3.5. Technical assessment

Given the specific area of application of GNSS systems in railways and the architecture of such a system, it is necessary to assess precisely whether the solutions meet the requirements for use in railway traffic. This poses a potential difficulty due to the divergence in the approach to the assessment of satellite systems versus railway systems. In GNSS nomenclature and environment, system performance is determined by the following criteria: accuracy, availability, continuity, and reliability. These criteria are mainly based on aeronautical applications and have been defined by the *International Civil Aviation Organization* (ICAO). They are not directly related to railway requirements criteria, which are usually classified in terms of R*eliability, Availability, Maintainability, and Safety* (RAMS). A common evaluation criterion in aeronautical systems regarding RAMS analysis is the concept of reliability. The significance of this concept in relation to railway applications can be defined in terms of all possible failures, the probability of failure, and the impact of failure on system performance. In both cases, reliability refers to the impact on the safety level of the assessed area of application. In addition, integrity is also a convergent concept when comparing ICAO assessment criteria and RAMS analysis. For satellite navigation users, integrity is a quantitative measure of confidence in the reported position. In railways, integrity means the ability of a safety system to provide correct, complete, and unaltered data or functions so that they cannot be accidentally or intentionally falsified. Integrity is one of the key attributes of functional safety and is directly related to *Safety Integrity Level* SIL levels, which define the acceptable probability of errors affecting safety. (Marais, Beugin, & Berbineau, A Survey of GNSS-Based Research and Developments for the European Railway Signaling, 2017).

According to Table 2, differences in interpretation mean that the use of satellite positioning systems in rail transport, which includes infrastructure, rolling stock, control, and energy, is not possible without first determining the priority and consistency of the assessment criteria in railways and aeronautics. To achieve this goal, it is necessary to:

1. Define consistent parameters for technical assessment criteria.
2. Considering and adapting different interpretations of the criteria.
3. Implement a uniform and consistent methodology at the interface between systems.
4. Develop a functional railway↔GNSS interface based on uniform technical assessment criteria.

### 3.6. ERTMS/ATO

The use of GNSS in ATO deserves attention. As shown above, GNSS communication with ERTMS takes place via the ETCS (RBC) system, which is responsible for the safety of rail traffic. Due to the development of CCS systems, including the implementation of automation of railway traffic management processes, e.g., ARS and ATO, as specified in the TSI specifications, there is an area that may be a prelude to further development and expansion of the use of a system such as GNSS. ATO is one example. This system is a solution that supports automatic train driving, which works as an addition to ETCS, focusing on operational efficiency, punctuality, and energy savings, while not being responsible for safety, which remains the responsibility of the ETCS system. ATO controls, among other things, traction, braking, stopping at destination points, and door opening, and its ATO-OB (on-board) and ATO-TS (track-side) components exchange operational data using defined communication interfaces, the specifications of which are found in documents Subset-125, Subset-126, Subset-130, and Subset-139. The relationship diagram is shown in Figure 9.

Table 2. Matrix of dependencies between RAMS and ICAO technical assessment criteria

| Criterion | RAMS | ICAO |
|---|---|---|
| safety | defined as the probability of a device or system functioning in a safe condition | - |
| continuity | - | describes the ability of the system to perform the initiated task of locating without any interference |
| accuracy | - | the degree of agreement between an estimated or measured value and the actual value |
| availability | determines the ability to maintain a functioning state in each environment in which it can perform the required function, assuming that the required external resources are provided | in terms of time, it determines the probability that the system is available at the start of a specific task related to object positioning; in terms of space (range), it determines the geographical area in which location information must be provided to the user/application |
| integrity | an element of the SIL assessment, i.e., the probability that the system will not perform its safety function incorrectly | describes the requirement that the system must independently detect and report failures |
| reliability | defines the ability of a device and system to perform specific functions at a specific time and under specific conditions | refers to applications in safety-related systems |
| maintainability | defines the ability to perform timely and easy maintenance (including servicing, inspection and control, repair, and/or modification) on the assumption that the operation is carried out in accordance with established procedures and measures | - |

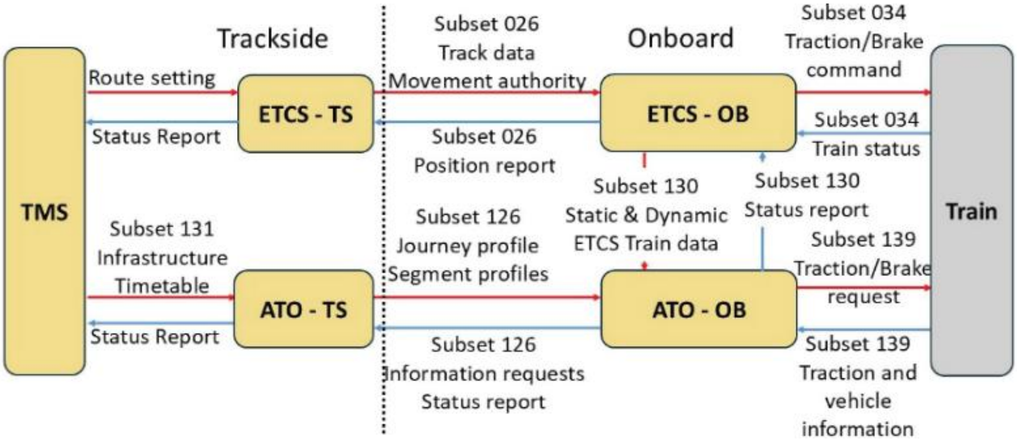


Fig. 9. Diagram of communication dependencies between ETCS and ATO modules (source: Tonk, Boussif, & El-Koursi, 2025)

Assuming that this system is not responsible for railway traffic safety, but only for improving the process of controlling trains moving on railway infrastructure, it can be assumed that in order to familiarize the railway market with satellite positioning systems, the use of GNSS for purposes such as correct train stopping in order to locate compartment entrances in strictly defined zones may be the basis and source of data for the process of implementing GNSS in railway traffic control. The best evidence to answer the question of the advisability and possibility of using GNSS in railway traffic control will be empirical experience, on the basis of which a series of studies, analyses, and simulations can be carried out to obtain factual conclusions for the purpose of determining how satellite positioning can be used in the safe operation of railway traffic. The successful implementation of satellite positioning in railway systems depends on the active involvement and cooperation of various stakeholders, including manufacturers, fleet operators, infrastructure developers, trade unions, civil society organizations, and government officials. Their joint commitment and cooperation are essential for the successful implementation and operation of GNSS systems. To meet these challenges, structural and cultural transformation is necessary to integrate the new technology, which will cause organizational and managerial complexity.

## 4. Positioning research

The research into the operation of GNSS systems included an analysis of their availability, accuracy, and functionality in various operating conditions. The aim was to assess the potential for using GNSS technology in railway applications, with particular emphasis on the requirements for availability, reliability, and positioning accuracy. However, the experiments were not limited to railway infrastructure. Some of the tests were also carried out using motor vehicles, which allowed for broadening the research context and comparing the results in different operating environments.

### 4.1. Location of rail vehicles within the infrastructure

Field research was carried out by taking a series of satellite positioning measurements, tracking the actual route of rail vehicles, speed, and weather conditions. In order to define the areas covered by the research, characteristic points were located, and the course of the railway line was mapped, which was compiled in tabular form and plotted on a topographic map.

Fig. 10. Location of reference points for measurement stations in the field – line no. 132 (left) and line no. 152 (right) (source: Author's own work)

Table 3. Example table of characteristic reference points for railway infrastructure

| Latitude | Longitude | Altitude | Time |
|---|---|---|---|
| 50,39748017 | 18,59687283 | 270,1000000 | 2024-07-20T08:35:35Z |
| 50,39755800 | 18,59675300 | 269,2870394 | 2024-07-20T08:35:46Z |
| 50,39767000 | 18,59657767 | 267,1362362 | 2024-07-20T08:36:01Z |
| 50,39776417 | 18,59640783 | 266,9077716 | 2024-07-20T08:36:16Z |
| 50,39788433 | 18,59621550 | 266,7059196 | 2024-07-20T08:36:28Z |
| 50,39799400 | 18,59604683 | 266,1239139 | 2024-07-20T08:36:39Z |
| 50,39807517 | 18,59591033 | 266,1975581 | 2024-07-20T08:36:47Z |

During the research, a locomotive equipped with a GNSS locator passed by, and its passage was recorded for the purposes of the research and analysis of the results. For the purposes of analyzing the field research, the locomotive's location data was used on the section from Pyskowice station to Paczyna junction. The results of the location, together with the reading of the locomotive's speed, are presented below in tabular form and on a topographic map.

The satellite data obtained on the location, time, and speed of the train were included in the analysis of the test results. For this purpose, the carrier's satellite data was read into the location measurement results for test sites no. 1 and no. 2 and projected onto a topographic map. The results are presented in the figure 10.

Table 4. Train location coordinates from the GNSS locator

| **Latitude** | **Longitude** | **Altitude** | **Time** |
|---|---|---|---|
| 50,39748017 | 18,59687283 | 270,1000000 | 2024-07-20T08:35:35Z |
| 50,39755800 | 18,59675300 | 269,2870394 | 2024-07-20T08:35:46Z |
| 50,39767000 | 18,59657767 | 267,1362362 | 2024-07-20T08:36:01Z |
| 50,39776417 | 18,59640783 | 266,9077716 | 2024-07-20T08:36:16Z |
| 50,39788433 | 18,59621550 | 266,7059196 | 2024-07-20T08:36:28Z |

Fig. 11. Mapping of GNSS locator coordinates relative to reference points line no.132 – station No. 1 (left) and station no. 2 (right) (source: Author's own work)

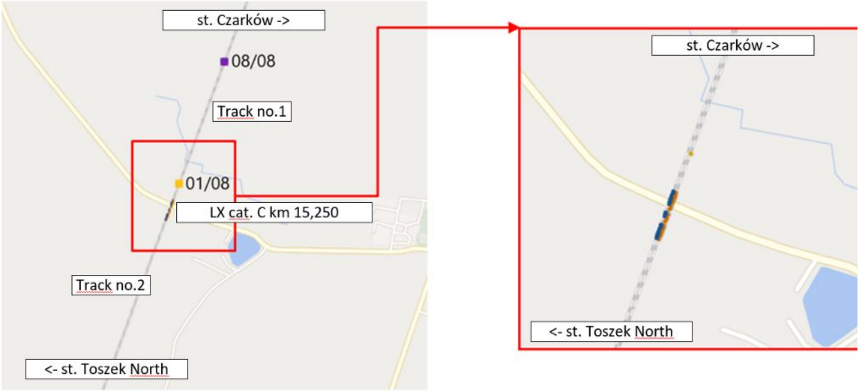


Fig. 12. Mapping of GNSS locator coordinates relative to reference points line no. 152 (source: Author's own work)

The research and data analysis carried out, in particular with regard to the research carried out on line no. 132, show that the level of accuracy of locating rail vehicles using satellite systems makes it possible to determine the location of a given vehicle on the railway infrastructure with a high degree of probability, even with the possibility of determining which track the vehicle is traveling on, as can be seen in Figure 11 for station no. 1. These research results provide a basis for conducting additional experiments.

### 4.2. Positioning of a moving vehicle

In the next stage, the research focused on measurements related to the analysis of the positioning accuracy of a moving object. For this purpose, mobile positioning devices were used, transported by a passenger car on designated sections of a provincial road and a motorway. The measurements were carried out by driving a passenger car on one section of a given road in two different directions at speeds ranging from 40 to 140 km/h, depending on the type of road. The research was supplemented by measurements of satellite system availability and atmospheric conditions in order to relate to the location data results. The results of the GNSS and atmospheric measurements are summarized in Table 5.

Table 5. Sample measurement results

| Measurement: | | | | | | |
|---|---|---|---|---|---|---|
| Speed [km/h] | 40 | 40 | 60 | 60 | 80 | 80 |
| Direction (N, S, E, W) | N | S | N | S | N | S |

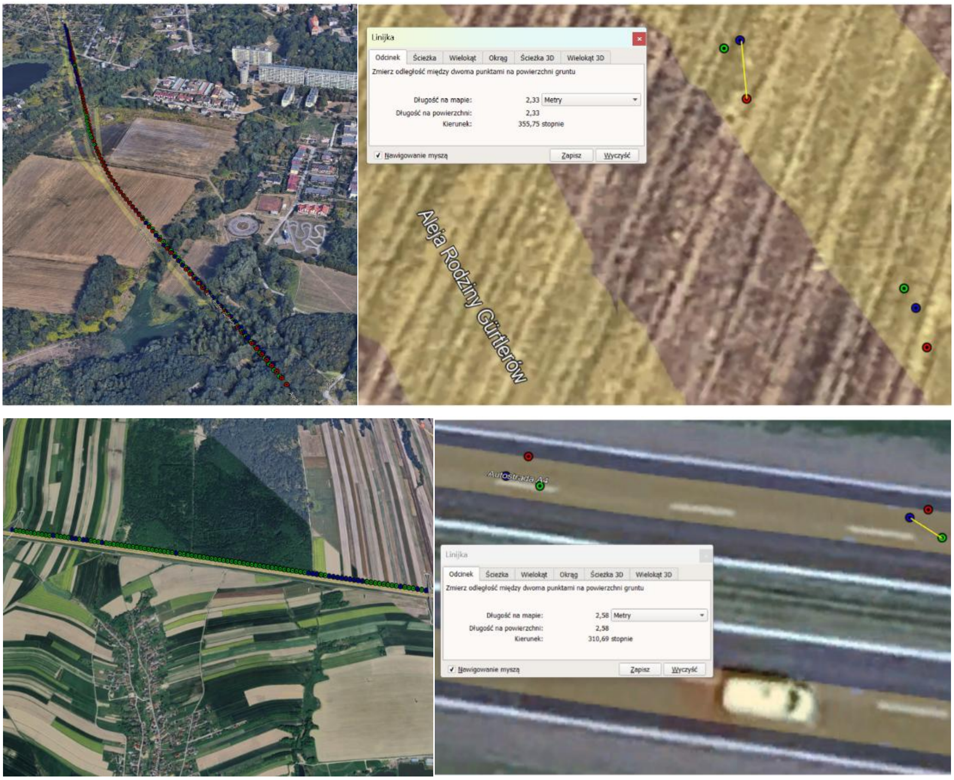
| Weather measurements: | | | |
|---|---|---|---|
| Time | 5:45 p.m. | 5:57 | 6:05 p.m. |
| Temp. [°C] | 19.0 | 18.3 | 18.5 |
| Humidity [%] | 46.1 | 40.8 | 57.2 |
| Pressure [hPa] | 972 | 972 | 972 |
| Wind [m/s] | 1.1 | 1.3 | 1.0 |
| Cloud cover [-] | average | average | average |

| Satellite measurements: | | | |
|---|---|---|---|
| Number of satellites within range [pcs.] | 37 | 36 | 36 |
| Number of satellites in the room [pcs.] | 19 | 21 | 19 |
| Horizontal accuracy [m] | 0.6 | 0.6 | 0.6 |
| Vertical accuracy [m] | 3.0 | 2.8 | 3.8 |

The results of satellite availability measurements for individual constellations and horizontal and vertical accuracy values given in meters presented in Table 5 are data obtained from the Status GNSS application.

In parallel with the measurements, the MATLAB Mobile application, installed on mobile location devices, was used during trips on designated sections. This application recorded the vehicle's location in real time based on satellite data, as well as data transmitted from mobile device sensors, i.e., accelerometers, gyroscopes, and magnetometers. The data obtained from the measurements made it possible to map individual journeys with the ability to reproduce characteristic parameters of vehicle movement, including speed, direction, location and altitude coordinates, etc. The data, processed using *Geographic Information System (GIS)* software, allowed for the visualization of the research, including the illustration of potential errors in vehicle location calculations resulting from the use of various mobile location devices, weather conditions, and the availability of GNSS signals in the area of the research. Sample visualizations and parametric imaging of measurement data are shown in Figure 13.

The research was supplemented by point measurements of so-called raw satellite system data. These measurements were taken at several different points in the vicinity of the areas described above and were made using the GnssLogger application installed on a mobile device. This application is used to record data from GNSS satellite navigation systems such as GPS, GLONASS, Galileo, and BeiDou. It allows the recording of raw data on satellite signals, such as signal strength, satellite ID, reception time, and pseudorange. Examples of data visualizations measured using GnssLogger are shown in Figure 14.



Zmierz odległość między dwoma punktami na powierzchni gruntu
Długość na mapie: 2,33 Metry
Długość na powierzchni: 2,33
Kierunek: 355,75 stopnie
☑ Nawigowanie myszą

Zmierz odległość między dwoma punktami na powierzchni gruntu
Długość na mapie: 2,58 Metry
Długość na powierzchni: 2,58
Kierunek: 310,69 stopnie
☑ Nawigowanie myszą

Fig. 13. Visualization of the results of measurements taken on a provincial road and a motorway (source: Author’s own work)

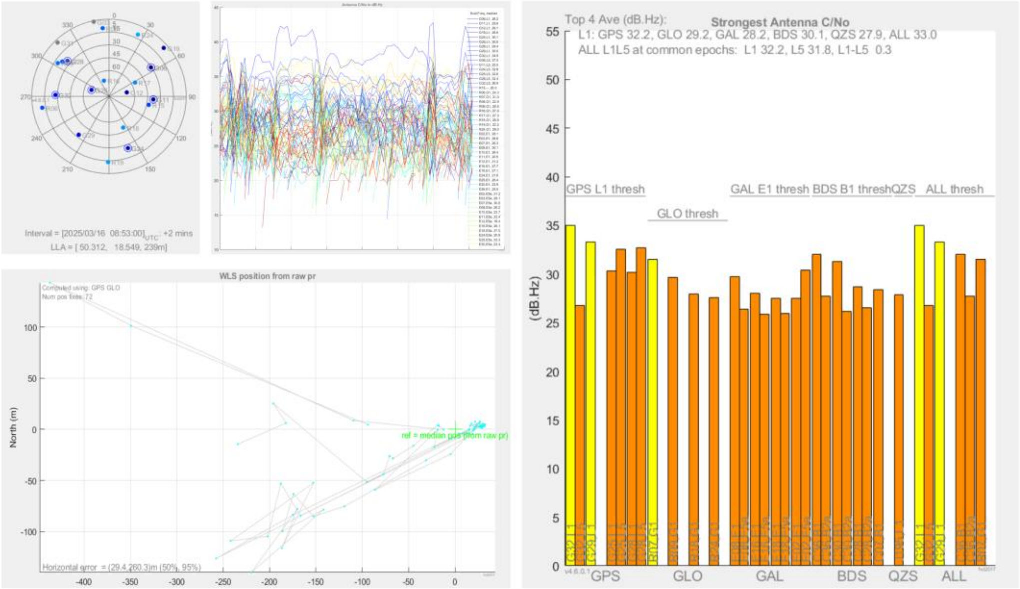


Fig. 14. Visualization of sample raw satellite system measurement data (source: Author’s own work)

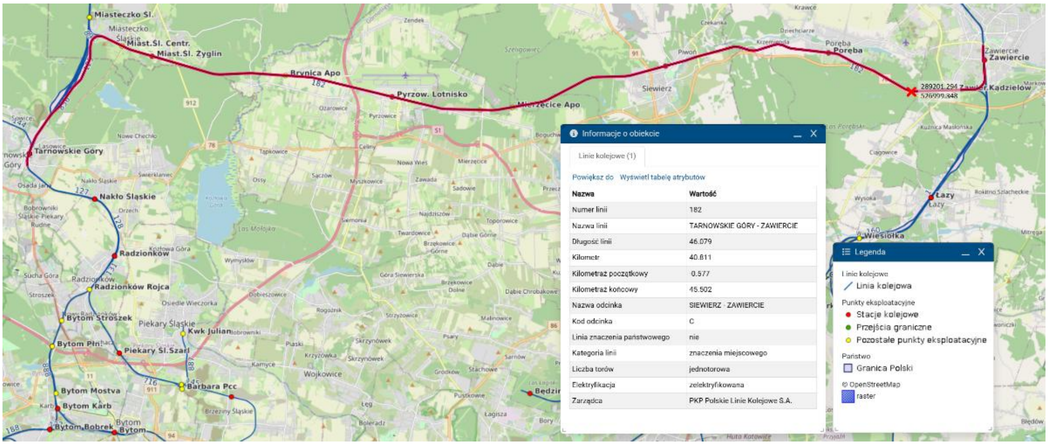
The same study presents research focused on measurements aimed at defining measurement methods, along with an assessment of the availability and accuracy of locating a moving object. The measurement results, conclusions, and observations made during the measurement activities were used to conduct research involving the location of rail vehicles on active railway infrastructure.

### 4.3. Positioning accuracy under operating conditions

Based on the research described above, tests were carried out to replicate those described in sections 3.1 and 3.2 under operating conditions of railway traffic. The tests in question were carried out on the line no. 182 Tarnowskie Góry-Zawiercie. The course of the railway line, together with the definition of operating points and basic line characteristics, is shown in Figure 15. It is worth noting that the line runs close to the International Airport Katowcie-Pyrzowice, which, in the context of the issue discussed in this publication, may serve as a kind of reference point for the potential use of GNNS systems in transport.

The operational tests consisted of several scheduled train journeys on line no. 182 between Tarnowskie Góry and Zawiercie. Before starting the measurements, the measuring equipment was calibrated using a CHCNAV i73 GNSS antenna. Then, based on the experience gained from previous tests, measurements were taken using the MATLAB Mobile and GnssLogger applications, whose measurement data was used to map the movement of individual trains on the railway line. The data obtained in this way allowed for a preliminary assessment of the reliability of mapping the location of a moving object in relation to the track infrastructure. The results of the analysis are shown in Figure 16.

According to the presented illustration, it can be concluded that the obtained test results allow for a preliminary mapping of the railway line by referring the location points of individual measuring devices to the course of the railway line. The above is the first step in the process of determining the suitability of using satellite positioning for rail vehicles. The next step in the process is a detailed analysis of the measurement results obtained. The above is presented by referring to location points in relation to the track infrastructure, in this case the track axis Figure 17.



Informacje o obiekcie

Linie kolejowe (1)

Powiększ do Wyświetl tabelę atrybutów

| Nazwa | Wartość |
|---|---|
| Numer linii | 182 |
| Nazwa linii | TARNOWSKIE GÓRY - ZAWIERCIE |
| Długość linii | 46.079 |
| Kilometr | 40.811 |
| Kilometraż początkowy | -0.577 |
| Kilometraż końcowy | 45.502 |
| Nazwa odcinka | SIEWIERZ - ZAWIERCIE |
| Kod odcinka | C |
| Linia znaczenia państwowego | nie |
| Kategoria linii | znaczenia miejscowego |
| Liczba torów | jednotorowa |
| Elektryfikacja | zelektryfikowana |
| Zarządca | PKP Polskie Linie Kolejowe S.A. |

Fig. 15. Route and general characteristics of railway line no. 182 (source: mapa.plk-sa.pl)

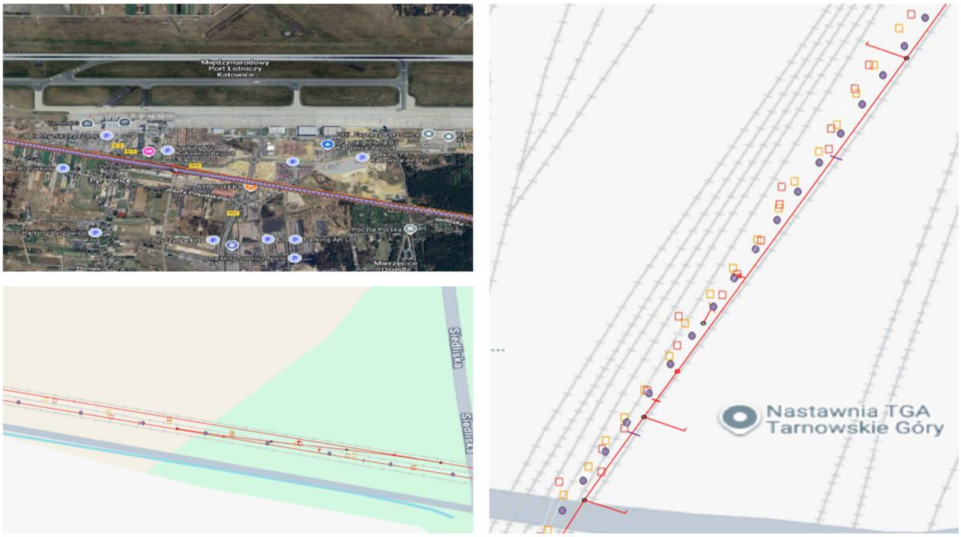
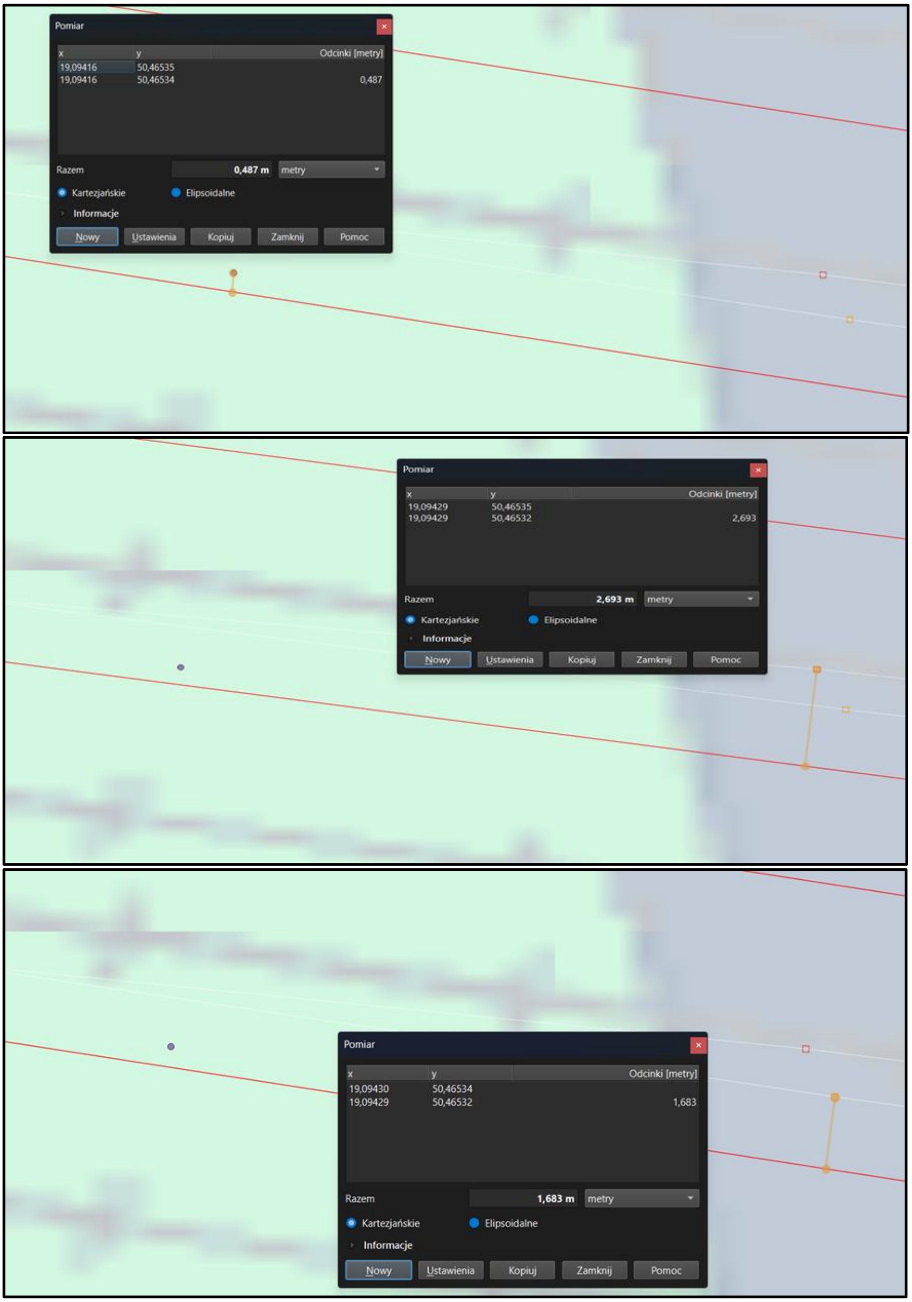


Fig. 16. Visualization of the results of location measurements of line no. 182 crossings (source: Author's own study)

As can be seen in the example analysis presented, the difference in measurement results relative to the track axis ranges from approx. 0.5 m to approx. 2.7 m. However, it should be noted here that the devices used for location measurements were not installed in the track axis, which means that in the further analysis of the results, an additional parameter resulting from this difference should be taken into account. Furthermore, analysis of the results showed that greater measurement accuracy was achieved when using the MATLAB Mobile application. Data from the GnssLogger application show a greater measurement error, even when corrections are applied using the built-in Kalman filter function. The above will be subject to further analysis as part of the ongoing research.



| x | y | Odcinki [metry] |
|---|---|---|
| 19,09416 | 50,46535 | |
| 19,09416 | 50,46534 | 0,487 |

Razem: 0,487 m, metry

● Kartezjańskie ● Elipsoidalne

| x | y | Odcinki [metry] |
|---|---|---|
| 19,09429 | 50,46535 | |
| 19,09429 | 50,46532 | 2,693 |

Razem: 2,693 m, metry

● Kartezjańskie ● Elipsoidalne

| x | y | Odcinki [metry] |
|---|---|---|
| 19,09430 | 50,46534 | |
| 19,09429 | 50,46532 | 1,683 |

Razem: 1,683 m, metry

● Kartezjańskie ● Elipsoidalne

Fig. 17. Example analysis of measurement results in relation to the track infrastructure – MATLAB Mobile (top), GnssLogger without Kalman filter (middle) and GnssLogger with Kalman filter (bottom) (source: Author's own work)

## 5. Conclusions

The subject matter of this publication, focused on increasing the efficiency of railway infrastructure use through the application of satellite systems for rail vehicle positioning, shows that the process of implementing GNSS in railway applications requires, above all, defining the area of use of satellite systems in systems related to Control-Command and Signalling. As demonstrated, it is necessary to determine the required level of confidence, which will determine whether the system will be used in the area of safe railway traffic management, or only to support railway traffic control, or in both areas simultaneously. The analysis presented here, and its conclusions justify the functional separation of GNSS as a subsystem providing reference data to other systems covered by the railway infrastructure. In this process, it is necessary to determine and define uniform and consistent assumptions for the assessment of technical criteria. Following the example of the guidelines and normative specifications being developed, it is necessary to prepare documentation specifying the assumptions for the implementation of Global Satellite Systems for Railways within the European Rail Traffic Management System ERTMS/GNSS-R.

When adopting the assumptions for the use of GNSS-R in each area of railway infrastructure, it is necessary to proceed to define the system architecture corresponding to specific guidelines and requirements. The process structure for communication between systems presented in the publication shows that GNSS-R system data can be used directly by ERTMS, TMS, and ATO systems or be a component of data transferred between ERTMS and TMS. This, as in the case of ATO, allows us to assume that for the purposes of properly determining the level of use of satellite systems in CCS, GoGNSS-R levels of GNSS-R implementation in railways can be used. The publication presents Multitracking GNSS as one of the architectures that could potentially be implemented. In addition to its basic benefits, which include increased positioning accuracy, this architecture has demonstrated features that enable additional functionalities related to monitoring the continuity of train composition. This solution can complement or replace TIMS, and additionally transmit information in the CCS system about a potential track event that may have occurred within the scope of this system. An additional benefit resulting from the use of GNSS in railways, particularly in the context of increasing efficiency, is presented in relation to an important factor affecting the throughput of a given railway junction, i.e., the time needed to set the train route.

As has been shown, this time significantly affects the occupancy of tracks and devices subject to a given route, and therefore the use of GNSS, which provides the dispatcher or ARS system with information on the exact location of a rail vehicle, allows for effective decision-making on the timing of route setting, which translates into increased capacity of a given railway junction.

The above functionalities, which make it possible to improve the railway transport process, can only be achieved if the GNSS-R system guarantees a high level of precision in locating rail vehicles within the railway infrastructure. The research presented in Section 3 illustrates the potential of GNSS in railways, but also the potential limitations of its use. Therefore, further research on the operation of the GNSS system within the track infrastructure is necessary to define and exclude the potential risks resulting from its implementation in railway signaling systems.

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