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Analysis of positioning methods using Global Navigation Satellite Systems (GNSS) in Polish State Railways (PKP)

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Abstract

Each year, global navigation satellite systems (GNSS) improve their accuracy, availability, continuity, integrity, and reliability. Due to these continual improvements, the systems are increasingly used in various modes of transport, including rail transport, the subject of this publication. GNSS are used for rail passenger information, rail traffic management, and rail traffic control. These applications differ in the positioning requirements that satellite navigation systems must meet. This article presents the methods and systems of rolling stock location and tracking using the Polish State Railways (PKP) as an example. The information on the equipment used for train positioning is not specified anywhere, hence they may differ, even for the same multiple units travelling in different parts of the country. In addition, the publication presents the progress of the European Train Control System (ETCS) implementation by the PKP.

Introduction

Global navigation satellite systems (GNSS) are widely used in various branches of transport, such as maritime, air, and land, including rail transport (Krasuski, Ćwiklak & Jafernik, 2018; Specht et al., 2019a; Specht et al., 2019d; Szot et al., 2019). Satellite systems can be applied in three major areas of rail transport: passenger information, rail traffic management, and rail traffic control (Chrzan & Jackowski, 2016; Specht & Koc, 2016; Czaplewski et al., 2019; Dąbrowski et al., 2019; Koc et al., 2019); however, satellite-based navigation systems must meet the accuracy requirements for train positioning.

The European Commission (EC) has financed several projects to implement satellite solutions for multiple unit positioning, including APOLO (Filip et al., 2001), GADEROS (Urech, Perez Diestro

& Gonzalez, 2002), LOCORPOL (Mertens, Franckart & Starck, 2003), GaLoROI (Manz et al., 2014), and 3inSat (Rispoli, Neri & Senesi, 2014), which have been developed in the last 10 years. However, none of these projects have developed a commercial product for the international market.

Positive train control (PTC) systems have been installed on most American rails since 2015. In its basic version, it uses global positioning system (GPS) satellites for train positioning, and is also supported by a ground-based augmentation system (GBAS), i.e. differential global positioning system (DGPS) (Betts et al., 2014; Specht et al., 2014; The Joint Council on Transit Wireless Communications, 2012). This system has a limited range because the DGPS system reference stations are located along the American coast, and their operating zone is less than 370 km (Specht et al., 2019c; Specht, Specht & Dąbrowski, 2019). Automated train management systems (ATMS) are being developed in Australia to reliably locate the first and the last train cars with an accuracy of no less than 2 m. As with the PTC system, this is accomplished by DGPS and GPS. The ATMS is planned to be installed on Australian rails by 2020 (ACIL Allen Consulting, 2019). The Chinese Train Control System (CTCS) is the equivalent of the European Rail Traffic Management System (ERTMS). The main difference between these two systems is that the CTCS uses BeiDou Navigation Satellite System (BDS) satellites to position trains (Ning et al., 2010; Lin, Wang & Dang, 2014; Junting, Jianwu & Yongzhi, 2016). BDS was chosen because it has more satellites (43) in orbit than any other GNSS, with a significant number (16) moving along geosynchronous orbits, which ensures continuous satellite communication with China (state as of March 2020).

This study presents rolling stock location and tracking systems, using the Polish State Railways (PKP) as an example. The information related to the equipment used for train positioning is not presented anywhere or regulated legally. Therefore, since it can be different even for the same units travelling in different parts of the country, this paper presents the current state of the train positioning system in Poland. However, the ETCS system is set to become the main rail transport positioning system in Europe.

Requirements for navigation satellite systems in rail transport

The quality of navigation systems is mainly classified by assessing navigation system parameters, which covers an established criteria space that is directly linked to previously-set navigation requirements. The comparative criteria of navigation systems presented in the literature are reassessed as the technology progresses and when the navigation process requires change, with a simultaneous change in the importance of each. The criterion analysis allows three groups to be identified that correspond to individual phases of the positioning system development (Dyrcz, Nitner & Specht, 2012):

- Position criteria – these characterise the positioning quality of the system and include three measures of the positioning accuracy (predictable, relative, repeatable); the operating zone; and frequency, unambiguity, and dimensionality of determinations;
- Reliability-related criteria – these are a separate group of indicators that refer to the reliability-related system operating characteristics, including availability, continuity, and reliability;
- Operation safety criteria – these are associated with providing up-to-date information on the quality (condition) of the system operation, thereby guaranteeing the proper operating level. To date, the only criterion in this group is integrity, characterised by a group of variables, such as time to alert (TTA), false alarm probability, etc.

These accuracy characteristics determine the possible applications of a specific GNSS. Table 1 presents the requirements of the positioning systems used in the ERTMS.

Table 1 shows that the European Geostationary Navigation Overlay Service (EGNOS) is currently

Table 1. The requirements for accuracy characteristics of virtual balises (Albanese et al., 2004)

Operating characteristics	ERTMS	RUNE
Positioning accuracy	5 m + 5% of the distance covered	3 m, $p = 0.95$ (GNSS + EGNOS)
Speed accuracy	2 km/h for $v < 30$ km/h 12 km/h for $v < 500$ km/h	2 km/h, $p = 0.95$ (GNSS + EGNOS)
Positioning availability	> 99% (level 3)	> 99%
Probability of correct system operation	> 99.9%	> 99.9%
TTA	< 5 s	< 5 s (level 3)

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the only positioning system that meets the majority of the navigation requirements (Marais, Beugin & Berbineau, 2017). The parameter describing the time between an incident of a system malfunctioning in its operating zone and the moment of passing the information to the system user is the TTA. Information on the system reliability is transferred only within the safety of life (SoL) service of the EGNOS system (Iwański & Toruń, 2006; Specht et al., 2019b). The service accuracy should not be lower than 3 m (p = 0.95) in the horizontal plane and 4 m (p = 0.95) in the vertical plane (GSA, 2019). Moreover, the SoL service should warn about a system failure within 6 seconds, which is 1 second more than required for the ERTMS system.

In the future, one of the Galileo system services will be an alternative for Europe; as with the EGNOS system, its tasks will send the user information on system malfunctions (Barbu & Marais, 2014). This is particularly important when a train goes through a tunnel or a densely built-up or afforested area, where the GNSS receiver tracks a smaller number of satellites, and the received satellite signal may contain a multipath error (Wohlfeil, 2011; Marais, Beugin & Berbineau, 2017). Ground- and satellite-based augmentation systems (GBAS/SBAS) can compensate for this using inertia measurements and odometry (travel and speed measured from wheels) in areas with low satellite visibility (Miettinen, Öörni & Lehtilä, 2018; Dąbrowski et al., 2020).

Train positioning systems in the PKP Szybka Kolej Miejska (SKM)

A train inspection regarding the devices used for multiple unit positioning by the PKP Szybka Kolej Miejska (SKM) in Tricity was conducted on 27.04.2019. SKM is part of the PKP Group, with shares in the company capital also held by local governments. The company was established in 2000 based on the liquidated Department of Fast Urban Railway. SKM manages rail line No. 250 between Gdańsk Śródmieście and Rumia (Figure 1). In 2018, the company renewed the contract for transport services in the Pomeranian Voivodeship until the end of 2022. SKM currently uses 69 railway vehicles, owns 59, and leases the others (diesel multiple units) from the Pomeranian Voivodeship.

In this study, an analysis was performed using several selected (available) trains operated by the PKP SKM in Gdynia Cisowa. The inspection involved a detailed assessment of multiple electric units whose main technical details are listed in Table 2.

EN57 trains are the longest series of railway vehicles in Poland; their manufacturing began in 1961 and ended in 1993, and the analysed multiple units were produced in 1987 (EN57AKM-1683 and EN57AKM-1693) and 1989 (EN57-1759). The two oldest trains were altered in 2014 when the drive system was changed. An EN57 multiple unit includes two control cars and one engine car (middle car). Multiple units can be coupled, but only

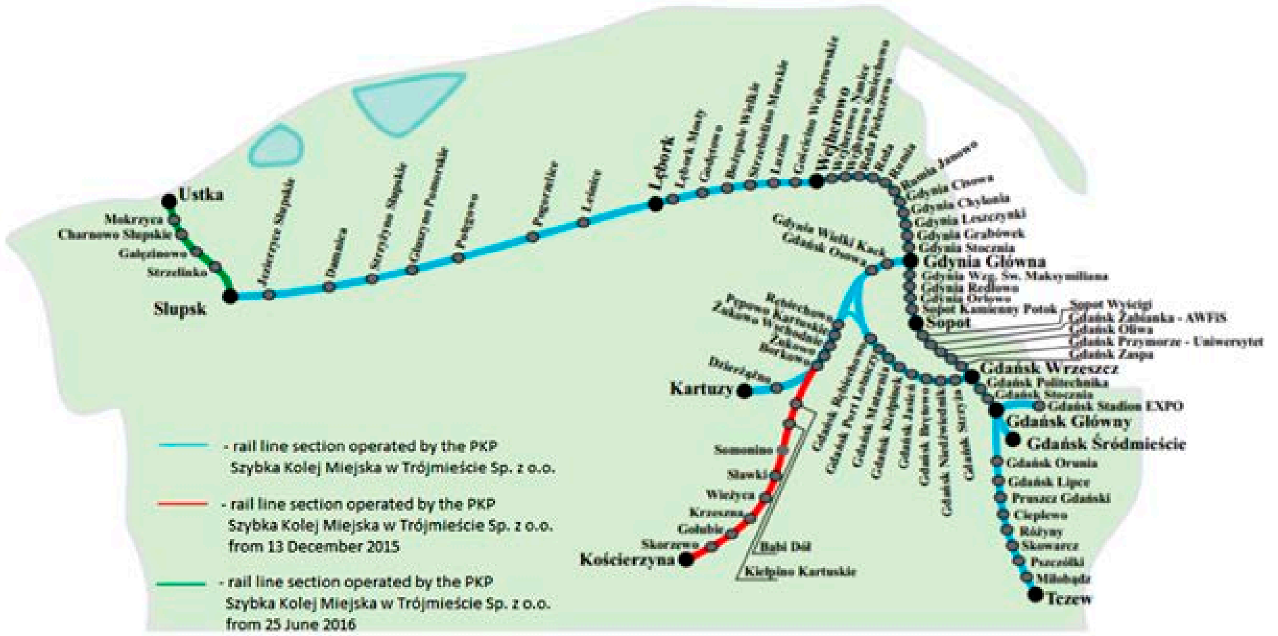

Figure 1. Network connections operated by the SKM Trójmiasto (SKM, 2019)

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Table 2. A list of main technical details of the analysed trains

Technical details	EN57	EN57AKM	EN71AC	31WE
Length	65 m	65 m	86.8 m	74 m
Total mass	124 t	124 t	182 t	135 t
Axle arrangement	2'2'+Bo'Bo'+2'2'	2'2'+Bo'Bo'+2'2'	2'2'+Bo'Bo'+ Bo'Bo'+2'2'	Bo'2'2'2'Bo
Engine power	4 × 145 kW	4 × 250 kW	8 × 250 kW	4 × 500 kW
Maximum speed	110 km/h	120 km/h	120 km/h	160 km/h
Number of doors	6 on a side + 2	6 on a side + 2	8 on a side + 2	8 on a side

in trains with the same drive system. The multiple units were located using a GNSS and the distance covered. GNSS antennas were mounted on the left side of the train, on the roof above the driver's cabin (Figure 2a). The AWIA SDIP passenger information system made by the ENTE was used in the multiple units (EN57AKM-1683 and EN57AKM-1693). Using data from the satellite receiver, the system updated the train timetable (displayed on the screen in the driver's cabin) (Figure 2b), making it possible to track the train on the route displayed on information boards installed in passenger compartments. In contrast, the EN57-1759 multiple unit was equipped with the XC-4 passenger information system made by Pixel, which – unlike the AWIA SDIP system – cannot update the train timetable or display it on a screen for the engine driver. The XC-4 system enables real-time train positioning (geographic coordinates expressed in decimal degrees) but, in practice, this information is not used by the driver during travel.

The EN71 train is a version of the EN57 train with an additional engine car. They were made by elongating existing EN57 multiple units in workshop conditions. The analysed vehicles were produced in 1976 (EN71-035) and 1977 (EN71-045). In 2009, the EN71-045 train was the only one in Poland to have its drive system modernised. An EN71 multiple unit includes two control cars and two engine cars (middle ones). The multiple units can be coupled, but only between trains with the same drive system (including with EN57). Locating the analysed multiple units was done using a GNSS and the distance covered. GNSS antennas were mounted on the right side of the train, on the roof above the driver's cabin (EN71-035) or the engine car (EN71-045). No timetable display for the driver was used in the EN71-035 multiple unit, and it was only equipped with the XC-4 on-board computer made by Pixel for route visualisation in the passenger information system (Figure 3a). In contrast, EN71-045 is equipped with a timetable display for the driver, made by the R&G, with an automatic positioning capability (Figure 3b), similar to the AWIA SDIP system.

31WE vehicles were the first modern trains purchased by the SKM Trójmiasto for use in line 250 in 2016. The multiple units under the trade name of Impuls were made by Newag in Nowy Sącz since 2012. The 31WE train consists of four segments, with the extreme segments fitted with engines. Multiple

(a) (b)

Figure 2. Position of the GNSS antenna mounted on the roof (a) and the ENTE train timetable display for the driver (b) in an EN57AKM-1693 train

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(a) (b)

Figure 3. The PIXEL on-board computer in the EN71-035 train (a) and the timetable display for the driver, made by the R&G, in the EN71-045 train (b)

units can be coupled, and locating the analysed multiple units is accomplished using a GNSS and the distance covered. GNSS antennas were mounted on the left side of the train, on the roof above the driver's cabin, similar to EN57 trains. The AWIA SDIP passenger information system made by ENTE, with automatic positioning capability, is used in multiple units of series 31WE-027.

European Train Control System (ETCS)

Both European and non-European countries are carrying out a project named ERTMS, whose aim is to harmonise railway traffic control systems (RTCSs). This initiative was launched because European countries use RTCSs with different applications and functions. For example, there are more than 20 railway signalling systems in the European Union (EU), which makes driving trains abroad difficult. This is because the engine driver must know the regulations applicable in a given territory and to have a thorough knowledge of the language of the country he/she is driving in. Moreover, the engine must be equipped in accordance with the railway board regulations and have its certificate of approval. This makes international railway service considerably difficult and can be improved by carrying out the ERTMS project (EP, Council of the European Union, 2013; EC, 2016; 2017).

One of the three main elements (along with the communications system and the traffic management system) of the project is the European Train Control System (ETCS), which is directly linked to train positioning (the subject of this study). The ETCS system is based on cab signalling, which enables visualizing the situation on the track on the display in the driver's cabin, rather than on the semaphore situated along the track. This is an advantage of the ETCS system because it can control the driver's response to messages on the track section. If the driver responds incorrectly, e.g., he ignores a "stop" signal, the train brakes will be engaged automatically. Moreover, if a driver does not notice all signals and warnings along the track when the train is travelling at a considerable speed, the ETCS system can take over (Ministry of Infrastructure and Transport of the Republic of Poland, 2017).

At the end of 2016, 90,000 km of rail lines and 12,000 vehicles met the ETCS system requirements. The obligation to implement the system applies only to rail lines in the EU Member States which are included in the Trans-European Transport Network (TEN-T), which is divided into the core and comprehensive networks. The comprehensive network includes all the existing and planned infrastructure elements of the TEN-T network, as well as measures supporting the effective social and environmentally sustainable use of this infrastructure. In contrast, the core network includes the parts of the comprehensive network with the greatest strategic importance for achieving the development objectives of the TEN-T network. The rail lines in the TEN-T network are required to implement the ERTMS/ETCS system on rail lines by the end of 2030 (core network) or 2050 (comprehensive network). Most European countries are currently on the second level (of three) of the system implementation (Rispoli, Siciliano & Brenna, 2017).

The train position in the ETCS level 2 is determined by two methods. The first (ETCS level 1) involves determining the train position using constant reference points called balises (Figure 4). These are electromagnetic devices that have the form of yellow containers, placed between rails near

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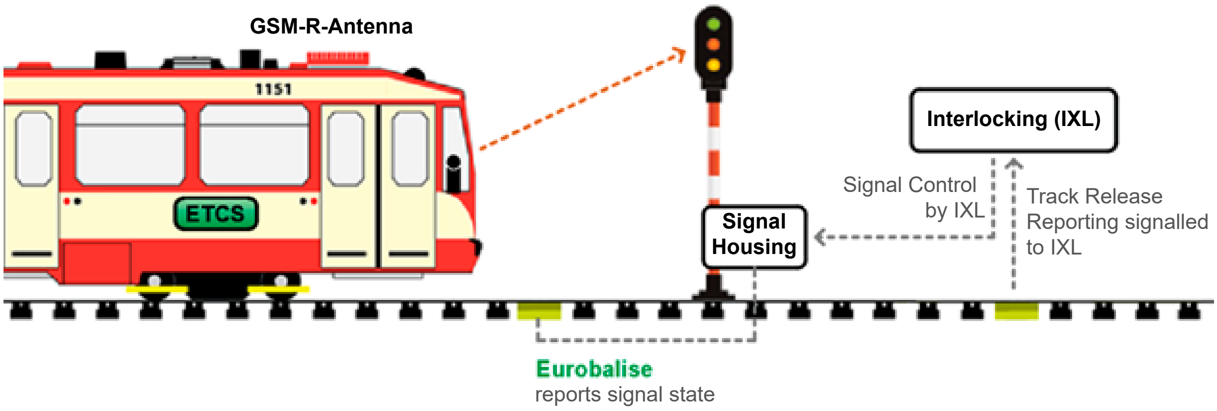

Figure 4. Information flow in the ETCS level 1 (Arrizabalaga et al., 2014; Thales Group, 2019)

semaphores (Figure 5a). Balises transfer information in the form of telegrams from line and station devices to an antenna on the train driving over a transponder (Figure 5b). Subsequently, the telegram is decoded, and the information it contains is transmitted to the on-board European Vital Computer (EVC). It is then verified and checked by the EVC, which sends it to the driver's imaging panel (Man-Machine Interface – MMI) (Toruń, Lewiński, 2010; Kulińska et al., 2017).

The other method involves train positioning using a radio block centre (RBC), which is a computer unit responsible for gathering information from the RTCS devices (line and station systems) and on-board devices of trains equipped with Euroradio. RBC analyses the gathered information and then continuously sends it to the train over the Global System for Mobile Communications – Railway (GSM-R) (Figure 6) (Toruń & Lewiński, 2010; Kulińska et al., 2017).

(a)

(b)

Figure 5. The balise (a) and an antenna under the engine to receive signals from balises (b)

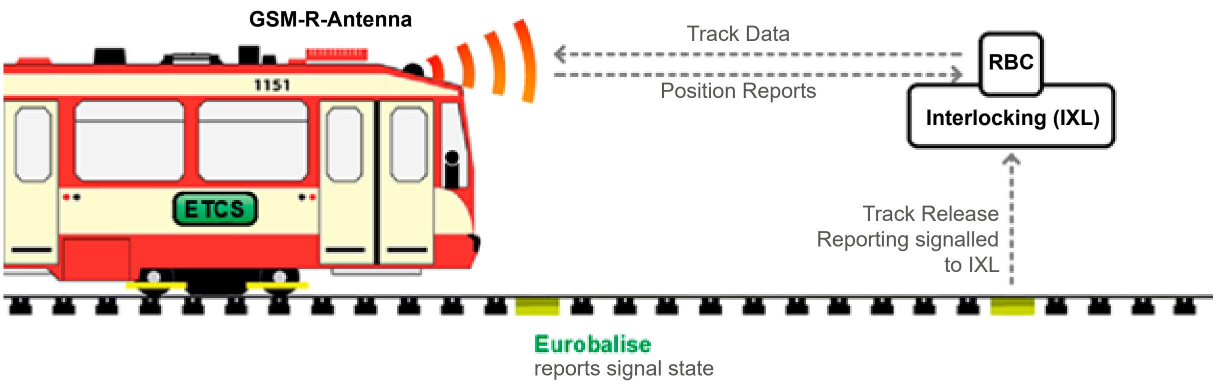

Figure 6. Information flow in the ETCS level 2. Own study based on (Arrizabalaga et al., 2014; Thales Group, 2019)

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The last and most technologically-advanced system for automatic railway traffic control is the ETCS level 3. Train positioning is performed using "virtual balises", which enable its location to be determined by GNSSs. This solution is beneficial from both an economic and functional point of view. Virtual balises provide greater cost savings than balises. Train positioning with GNSSs does not require any railway equipment, and the number of conventional balises installed on the track can be limited to places where positioning requirements are not met. This is important because the cost of installing the trackside part of the ECTS level 2 is ca. PLN 0.5 million per 1 km of track. This is increased by annual maintenance costs, which amount to ca. PLN 20 thousand per 1 km of track for ETCS level 2. Therefore, it is economically justified to use GNSSs for multiple unit positioning, but some costs must be incurred in connection with implementing the GSM-R system, which is an essential part of ETCS levels 2 and 3. In 2016, the European Union Agency for Railways (ERA) estimated that the cost of system implementation was PLN 200,000 – 250,000 per 1 km of track, and its annual maintenance cost was PLN 4,300. Another functional benefit of ETCS level 3, is the possibility of continuous, real-time train positioning, unlike in levels 1 and 2, where multiple unit coordinates are determined at specific points – balises. Moreover, ETCS level 3 does not require traffic lights or devices to detect if a track is occupied because the train operator controls it with the on-board computer (Figure 7) (Toruń & Lewiński, 2010; Kulińska et al., 2017; Ministry of Infrastructure and Transport of the Republic of Poland, 2017).

The train coordinates for ETCS level 3 are calculated from data obtained from the GNSS antenna installed in the driver's cabin or on the multiple unit roof (Manz et al., 2014). The EGNOS system is used in Europe in train positioning, along with the Galileo system, which is gradually being introduced (Marais, Beugin & Berbineau, 2017; Rispoli, Siciliano & Brenna, 2017). Both satellite systems have been previously used in train positioning as part of the RUNE (Albanese et al., 2004; Marradi, Albanese & Di Raimondo, 2008) and ERSAT projects (Facchinetti, Ansalone & Tuozzi, 2015). Compared with levels 1 and 2, multiple units are also equipped with train integrity units (TIU) which are responsible for analysing the integrity of the data (the distance covered, current devices readings, and actual train drive parameters) recorded by the on-bard ETCS system devices, which communicate continuously with the RBC over the GSM-R radio channel (Kulińska et al., 2017).

Apart from the previously-mentioned GNSS antenna – which is usually mounted on the multiple unit roof but sometimes in the driver's cabin – there another noteworthy sensor: an odometer. This device is used to measure the distance covered by the train (Bai-Gen et al., 2009). Alternatively, eddy current sensors are used to measure the distance covered by a multiple unit instead of an odometer (Bohringer & Geistler, 2006; Hensel, Hasberg & Stiller, 2011; Manz et al., 2015). The positioning system can also be aided with inertial measurement units (IMU), such as a gyroscope or an accelerometer (Marais, Beugin & Berbineau, 2017). The data recorded by all devices are processed (integrated) and used to determine at which signal block the train is located. This is important because to ensure railway traffic safety, there can be only one multiple unit in each signal block, i.e. between two semaphores. Therefore, it is important to have multiple sensors (including some double ones) for accurate and reliable train positioning (Stallo et al., 2018; Stallo et al., 2019).

PKP is responsible for implementing the ETCS system in Poland. According to the national implementation plan for the ERTMS system, ETCS level 1 is expected to be implemented on 3,555 km

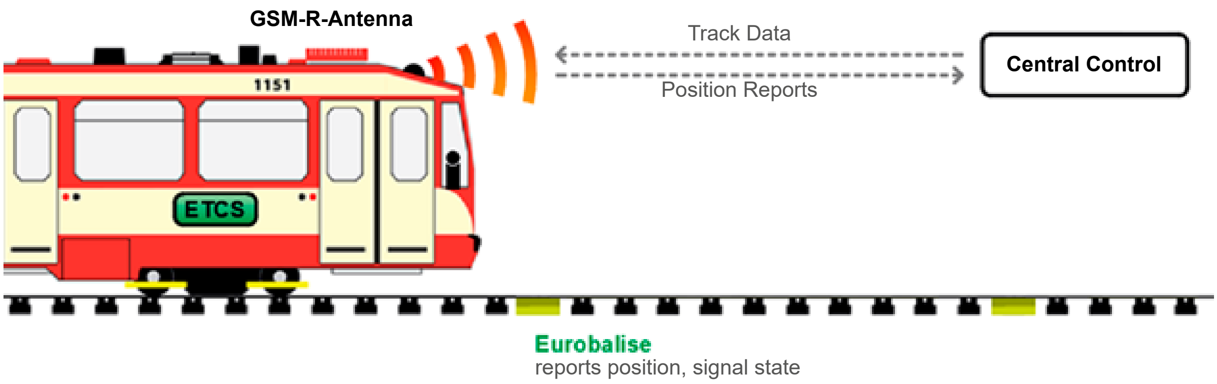

Figure 7. Information flow in the ETCS level 3. Own study based on (Rispoli, Siciliano & Brenna, 2017; Thales Group, 2019)

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of rail lines, and ETCS level 2 on 4,678 km of rail lines in Poland. Apart from the ETCS system track-side equipment, devices should also be installed on trains so that the system functions properly. Nearly 1,513 engines and multiple units are expected to be equipped with the ETCS system essential infrastructure. Currently, the ETCS system in Poland has been implemented on 331 km of rail lines, which accounts for a mere 7% of the total rail length included in the plan. Moreover, there are only 145 multiple units equipped with the ETCS system approved for use on Polish rail lines. Detailed information regarding this issue is presented in Table 3 (Ministry of Infrastructure and Transport of the Republic of Poland, 2017).

Table 3. A list of Polish rail lines in which implementation of the ETCS system has been completed (Ministry of Infrastructure and Transport of the Republic of Poland, 2017)

Line number	Initial station	Final station	Length [km]	Level
4	Grodzisk Mazowiecki	Zawiercie	224	L1
64	Kozłów	Starzyny	33	L1
282	Miłkowice	Węgliniec	62	L2
295	Węgliniec	Bielawa Dolna	12	L2

Conclusions

This analysis has shown that trains in Poland are not equipped with a uniform positioning system. Examination of the multiple units operated by SKM Trójmiasto showed that the older models (EN57-1759 and EN71-035) are not equipped with driver's timetable displays, only with on-board computers for route visualisation of the passenger information system. In contrast, new (31WE-027) or modernised (EN57AKM-1683, EN57AKM-1693, and EN71-045) trains are equipped with both timetable displays for the driver and on-board computers. During the visit to the PKP SKM premises in Gdynia Cisowa, we noticed that the location and type of GNSS receivers in trains in Poland were not uniform and varies even within one multiple unit. Satellite antennas were mounted in various ways on trains, and the majority were mounted on the left and right sides of the multiple unit, on the roof of the driver's cabin. No information on the type of GNSS receivers used was available during the inspection. One may suppose that these are multi-systems, code satellite receivers with several-metre positioning accuracy. For railway applications, it seems reasonable to use augmentation systems such as EGNOS because they provide users with information about the integrity. Together with other IMUs, such as accelerometers or gyroscopes, they can be useful for determining train positions in areas with impaired satellite visibility, such as tunnels, urban areas, or forests.

European countries are carrying out a project entitled ERTMS, whose aim is to harmonise railway traffic control systems. One of the three main elements (along with the communications system and the traffic management layer) of the project is the ETCS, which is directly linked to train positioning. The project assumes that multiple unit positioning in Europe can be accomplished using the EGNOS/Galileo systems or with conventional/virtual balises within a dozen/several dozen years. The implementation costs for the ETCS are prohibitively expensive for some European countries. For example, the implementation cost of the ETCS level 2 amounts to ca. PLN 700,000–750,000 per 1 km of track, which is increased by annual maintenance costs, which amount to ca. PLN 25,000 per 1 km of track. The ETCS system in Poland has been implemented on 331 km of rail lines, which accounts for a mere 7% of the total length of railways included in the plan. Moreover, there are only 145 multiple units equipped with the ETCS system out of the planned number of 1,513 approved for use on Polish rail lines.

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