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ETCS/ERTMS – A UNIFIED RAILWAY TRAFFIC CONTROL SYSTEM AFFECTING RAILWAY LINE CAPACITY

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Abstract – The aim of this article is to present the architecture and analyze the functionality of the European Rail Traffic Management System ERTMS/ETCS, which is a unified railway traffic management system that increases railway line capacity compared to current railway traffic control systems, by presenting its methodology and impact on railway traffic safety, which has a higher level in transport tasks.

Keywords – ERTMS/ETCS, moving block sections, capacity, safety

INTRODUCTION

The European Train Control System (ETCS) represents one of the most advanced and comprehensive railway traffic control solutions currently being implemented across Europe. According to European Union regulations, standards, and directives - particularly those forming the basis of the European Rail Traffic Management System (ERTMS) - all EU member states are obliged to adopt this system on their national railway networks. ETCS serves as a unified, interoperable supervisory framework designed to manage and monitor train operations while meeting stringent safety, reliability, and capacity requirements. Its operation relies heavily on digital data transmission between trackside infrastructure and onboard vehicle systems, enabling efficient and secure communication throughout railway operations. One of the key strengths of ETCS lies in its use of continuous digital communication, especially at higher system levels such as ETCS Level 2. This form of communication allows rolling stock to operate without the interoperability issues associated with older, country-specific systems - problems such as inconsistent software architectures, incompatible signaling technologies, and unreliable data transfer protocols. By utilizing standardized digital interfaces and modern radio communication technology, ETCS ensures seamless cross-border train movement, thereby eliminating many of the historical barriers to international rail traffic in Europe. The primary objective of implementing ETCS is to increase the capacity of railway lines while simultaneously maintaining the highest possible level of operational safety. The system achieves this through real-time train supervision, precise movement authority calculations, and continuous speed monitoring. However, improvements in line capacity and safety are not the only advantages. ETCS also contributes to enhancing the overall competitiveness of rail transport relative to road and air transport. By enabling trains to travel at optimized speeds with minimal delays, the system significantly reduces travel times for both passengers and freight. This makes rail transport a more attractive option for logistics operators and travelers seeking reliable and time-efficient transport solutions. From an environmental perspective, the expansion of rail transport is particularly beneficial. Railways are capable of carrying large quantities of goods in a single transport task, which results in considerably lower emissions per ton-kilometer compared to other modes of transport. Consequently, increasing the share of rail transport within the broader European transport network supports the EU's long-term climate and sustainability objectives. This is especially relevant at a time when economic growth within the European Union - despite challenges such as the COVID-19 pandemic and the ongoing Russian-Ukrainian conflict - continues to drive up demand for the movement of goods and people. The geopolitical crisis in Eastern Europe has highlighted yet another advantage of rail transport: its resilience and safety in times of instability. The gradual implementation of the ERTMS/ETCS system across European railway corridors is intended to ensure efficient, uninterrupted train movement within the EU's internal market. Although the development and installation of ETCS infrastructure require substantial financial investments, the long-term benefits outweigh the initial costs. By significantly increasing the capacity of railway lines - beyond what is achievable using legacy traffic control systems - the system enables more trains to operate safely, thus increasing revenue potential for railway operators. Additionally, improved operational efficiency contributes to lower long-term maintenance and operational costs. It is important to note that ETCS implementation is not only mandated by EU legislation but is already required for newly constructed or modernized railway lines and rolling stock. The deployment process encompasses both trackside installation - such as balises, radio block centers (RBCs), and advanced signaling equipment located in control centers - and the installation of onboard systems in locomotive driver's cabs. These onboard components ensure that drivers receive real-time information regarding speed limits, movement authority, and track conditions. While this generates significant expenses for railway carriers, it also creates opportunities for modernization, standardization, and improved interoperability.

Successful implementation of ERTMS/ETCS requires close cooperation between railway infrastructure managers and train operating companies. Coordinated progress is essential; without it, one part of the system may advance faster than the other, potentially hindering the overall benefits of interoperability. When both parties synchronize their modernization efforts, the full potential of ERTMS/ETCS - faster operations, higher safety standards, and seamless cross-border traffic - can be realized.

At its core, ETCS Level 2 relies on the GSM-R radio communication system, which enables continuous communication between trains and radio block centers. This advanced communication architecture shifts some operational responsibility to the train driver while reducing the likelihood of human error through automated supervision. It also provides a dynamic and accurate real-time overview of traffic conditions across entire railway lines, significantly improving the overall management of train movements.

Although railway traffic control systems have existed since the early days of railways, evolving transportation demands, growing traffic volumes, and modern safety expectations continue to necessitate technological advancements. The development and gradual rollout of sophisticated signaling and control solutions - such as ETCS - reflect the ongoing effort to optimize train operations, improve service quality, and ensure the safe and efficient performance of transport tasks across Europe.

1 EUROPEAN TRAIN CONTROL SYSTEM ETCS/ERTMS – STRUCTURE AND FUNCTIONING

The European Railway Traffic Control System (ETCS) addresses the need to implement uniform and more advanced methods of rail traffic management. Many publications emphasize that its primary purpose is to ensure safe rolling stock operation while simultaneously increasing line capacity through continuous digital information transmission between trains and the infrastructure [1, 5, 12]. The system's design combines cab signaling with driver supervision, significantly reducing the risk of human error. This approach is also widely discussed in publications from the Warsaw University of Technology, which indicate that ETCS changes the philosophy of rail traffic management – from systems based on light signal observation to a system of continuous data exchange [58, 59]. The system operates fully digitally and utilizes various information transmission channels, depending on the ETCS level implemented. Eurobalises, Euroloops, and GSM-R constitute a set of tools enabling the transmission of movement authorizations, speed profiles, and train position. Researchers point out that only the integration of GSM-R radio data transmission with the ETCS system creates ERTMS – the European Rail Traffic Management System, which ensures interoperability in all EU countries [17, 19, 23, 58]. This enables the transmission of detailed data, including information on permitted speeds, restrictions resulting from track geometry, and current traffic conditions. The cab signaling provided by the system continuously significantly exceeds the capabilities of classic semaphores, while simultaneously reducing the need to monitor trackside infrastructure in conditions of limited visibility [11, 32]. Publications by WUT experts and the work of Professor Kochan emphasize that the modern ETCS architecture allows for the construction of a much more efficient rail traffic system, as the constraints are no longer fixed block spacing, but rather the quality of data transmission and the speed of information processing [58, 59]. In practice, this means shortening the distances between trains and enabling more flexible train routing. This is particularly important on lines with high traffic volume, where every meter of saved headway affects the number of trains that can be passed in a given time period. The literature points out that traditional systems based on line blocking still fulfill their function, but have a limited ability to increase throughput. Light signals displayed to the driver only convey partial information, and the response to them depends on weather conditions and human perception. ETCS solves this problem by transmitting all key driving parameters to the driver's cab, such as speed profile, minimum braking distance, and closed sections [3, 4, 17]. This allows the system to dynamically adjust the movement authorization to the current track situation. A major advantage of ETCS is its interoperability. Trains equipped with the system can cross international borders without the need to change locomotives or on-board modules, significantly shortening travel times and facilitating traffic organization [17, 23]. This enables uniform passenger and freight traffic throughout the European Union, as confirmed by UIC reports and numerous publications describing implementations on high-speed lines and freight main lines [19, 22, 24]. The Warsaw University of Technology (WUT) repeatedly emphasizes that interoperability is the foundation of modern rail transport and a condition for rail's competitiveness with road transport [58]. The design of the ETCS structure takes into account the specificity of each section of a railway line. Stations, traffic control points, regional and main lines differ in their characteristics, therefore the system requires individual parameter configuration to operate effectively. The literature indicates that determining line capacity requires a thorough analysis of variables such as train sequence time, travel time, and the degree of utilization of the available infrastructure [6, 25, 30]. This, in turn, influences the selection of ETCS devices and system architecture, which must be adapted to both technical and organizational conditions. The Warsaw University of Technology (WUT) studies particularly emphasize that line capacity depends on its "weakest link." Even the best control system will not increase capacity beyond the level provided by the busiest section of the line [21, 59]. Therefore, it is crucial that modernization encompasses not only the implementation of ETCS, but also the entire infrastructure, the condition of which determines the capabilities of the control system. Analyses also point to the role of usable capacity, which takes into account not only technical capabilities but also time reserves, reliability, and economic factors [16, 20]. In the case of ETCS Level 3, a significant reduction in time reserves can be observed, as block headways are variable and depend on the actual train position, not on fixed track sections [16, 22]. However, the authors of numerous publications point out that even the most advanced technology must comply with national regulations, such as PKP PLK S.A. Instruction Ir-1, specifying minimum safety requirements [Instruction R-1]. Therefore, designing an ETCS object-oriented application must take into account both the potential for increased capacity and the requirements of national regulations. The topic of the maximum capacity utilization factor γ also appears in the literature. It is used to assess how close a given railway line is operating to its maximum capacity and how ETCS implementation can improve this factor. Many studies have shown that the system can significantly increase the γ factor on lines with high traffic intensity, which is confirmed by both European practice and analyses conducted in Poland [17, 20, 21, 31, 58]. When analyzing railway line capacity, it's worth noting that, similarly to mechanical engineering, a device's reliability depends on its weakest link. The same relationship applies to railway line capacity, as capacity depends on the railway line sections and can never exceed the capacity of any of the sections subjected to system analysis [8]. Maximum railway line capacity is achieved when the highest throughput and technical efficiency of railway traffic control equipment can be observed, with appropriate implementation and organization of transport system technologies and the transport cycle. Another parameter worth mentioning when analyzing line capacity is usable capacity. This determines the capacity obtained by taking into account reliability and economic factors that may arise during formal analyses, including time reserves [15, 30]. In the case of passenger traffic, when analyzing capacity, it is also worth considering the number of passengers transported at a given time, taking into account higher traffic intensity and reduced demand for rail transport services. Such an overview is possible primarily on railway line sections designated for passenger traffic. The technical devices that determine the capacity of traction sections subjected to traffic optimization are railway routes and stations, where two types of rail traffic can be distinguished: station traffic and route traffic. All of these factors significantly influence the installation of information devices for train drivers and the transmission of information regarding rail traffic control from trackside (external) devices. This is an important element used in the design of the ETCS/ERTMS system, as the correct definition of these parameters also influences the proper operation of the system and allows for the configuration of devices used for communication and information transfer on a given railway line. Analyzing the functionality of the ETCS system, a reduction in time reserves can be observed, particularly in the case of level three, where variable block headways can be considered. Thanks to their design, these headways allow for shortening the intervals between trains through appropriate communication levels. However, it is worth noting that distances on the track and in the station cannot be too small, even if the technical system allows for shortening distances, but they cannot be shorter than specified in the Ir-1 (R-1) railway instruction on the operation of rail vehicles, published by PKP PLK S.A. In order to determine the appropriate ratio of the throughput marked as *N* to the analyzed maximum throughput N_{MAX}, the maximum throughput utilization factor marked as γ can be determined [6, 17, 30].

The formula (1) is the quotient of the indicated data [1]:

$$\gamma = \frac{N}{N_{MAX}} \tag{1}$$

where, according to the above information:

γ – is the coefficient of utilization of maximum capacity, expressed as the ratio of the number of trains passing on the analyzed route or railway line that have completed the entire journey specified in the transport task,

N – is the capacity coefficient expressed in the number of trains per day,

N_{MAX} – maximum capacity expressed as the number of trains per day.

The structure of each railway line is also presented and analyzed in terms of maximum train capacity. It depends on the succession times of trains performing their transport tasks on the line and constitutes the time needed to cover the so-called succession distance.

When analyzing the capacity of a railway line, it is important to take into account the intervals between two trains that may occur, where the aim is also to minimize them. Railway regulations define specific lengths of intervals that should occur between trains running one after another, but the ETCS system makes it possible to reduce distances provided that there is no conflicting movement on the track section. When two trains are running and there is a risk of collision, it is necessary to maintain a time interval, which in railway terminology is referred to as the station sequence time. Sequences occur in three cases, the most common of which is when trains are not accepted simultaneously. The second case in which we can consider sequences is when trains are dispatched. The third aspect combines both cases of time sequence, in which case we refer to the non-simultaneous arrival and departure of trains. Station train path intervals, represented as L_p, can be determined using formula (2) [1]:

$$L_p = \frac{l_p}{2} + l_{s|o} + l_b + l_r \tag{2}$$

where:

L_p – is the station distance expressed in meters (m),

l_p – is the train length expressed in meters (m),

$l_{s/o}$ – is the distance between the station axis and the entry signal expressed in meters (m),
l_b – is the length of the block interval equal to the distance between the last block signal and the entry signal, expressed in meters (m),
l_r – is the distance traveled by the train in a time equal to the driver's reaction time to a noticed signal, or the visibility distance expressed in meters (m).

Using the above formula (2), it is possible to determine the station distance using standard railway traffic control systems, where the schematic diagram of the implementation of the runs can be carried out in accordance with Figure 1.

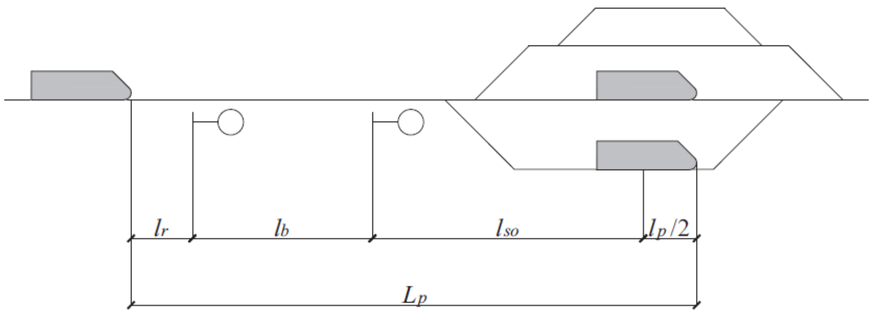

Figure 1. Schematic diagram of the distance between trains at a station [8]

However, it is worth noting that when using the ETCS system on the line and at the station, the dependencies for determining the station distance (L_{pETCS}) are based on similar but different dependencies. They can be calculated using formula (3):

$$L_{pETCS} = \frac{l_p}{2} + l_{so} + l_b + l_{rETCS} \quad (3)$$

where:
L_{pETCS} – station distance for a station equipped with the ETCS system (m),
l_{rETCS} – distance traveled by the train while information is being transmitted to the driver's cab and while the driver is responding to the information on the console (m),
l_p – is the length of the train expressed in meters (m),
$l_{s/o}$ – the distance between the station axis and the entry signal expressed in meters (m).

When the ETCS system is used on a line, the schematic diagram of station and block runs differs significantly, making it possible to obtain a more accurate analysis of rail traffic, while at the same time enabling runs to be managed in a much safer way for rail traffic, increasing throughput and reducing the risk of collisions. Figure 2 presents a schematic diagram of the determination of the distance between trains in station traffic with the ETCS/ERTMS system installed.

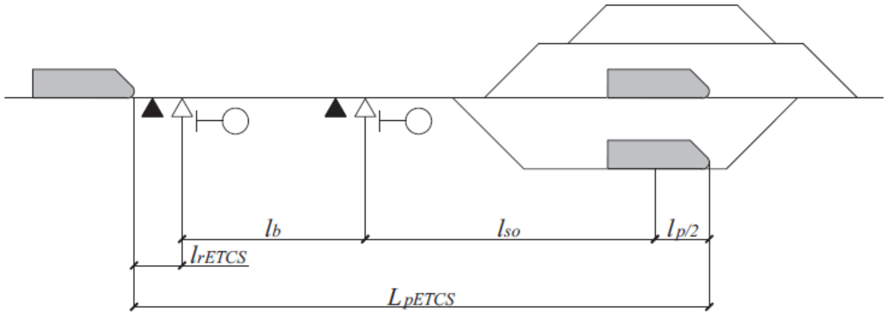

Figure 2. Schematic diagram of the distance between trains at a station equipped with the ETCS/ERTMS system [8]

Figure 2 above shows the differences in the operation of various railway traffic management systems compared to the ETCS system. The ETCS/ERTMS system has implementation levels that determine its functionality and hardware equipment, which also represent the technical sophistication of the devices with which the railway line is equipped. The levels, according to their implementation stages, have a significant impact on the capacity of the railway line and the methodology of station and block traffic management, where in the case of level 3 implementation of the ETCS/ERTMS level 3, there is also an assumption to change standard block sections to variable block sections, which allow for an increase in railway line capacity by reducing the distance between trains running one after another [16, 30].

2 MOVING BLOCK SECTIONS AS ELEMENTS ENSURING A HIGH LEVEL OF SAFETY AND CAPACITY IN THE ERTMS/ETCS SYSTEM

In the ERTMS/ETCS system at implementation level 3, we are talking about variable block sections, which are a more sophisticated modern alternative to the fixed block sections currently used in standard railway traffic control systems [1, 2, 7, 23]. It is worth noting that fixed block sections, as the name suggests, divide the railway line into fixed, appropriately divided track sections, which have a specific length that cannot be changed, and their beginning and end are determined by semaphores located next to the tracks [9, 10, 23]. Fixed block sections operate as follows: when a given block section is occupied by rolling stock, the lights on the semaphores change, because according to current regulations, there must be a distance difference of one block interval between trains traveling on the route, so when a train approaching the next block section sees a red signal "stop" signal, which does not allow it to continue until the train in front of it has cleared the block section with a difference of plus one [3, 10, 23]. It will only receive a signal change allowing it to proceed when the train in front of it has cleared the block section. In this case, the line capacity is limited by conditions related to the safety of railway traffic [1, 9]. The operation of fixed block sections is shown in Figure 3. It describes how block sections are occupied by trains traveling simultaneously in the same direction using standard light signaling [4, 16]. It shows the train running pattern according to the standard traffic control system, where safety conditions and regulations result from analyses of track vacancy detection systems and traffic control systems [5, 6, 12, 22].

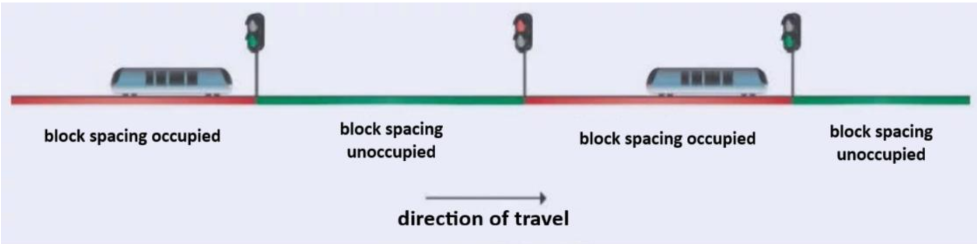

Figure 3. Diagram of fixed block sections [23]

The ETCS/ERTMS system at implementation level 3 proposes an alternative to the fixed block sections mentioned above in the form of mobile block sections, based on the implementation of tasks on routes using radio communication. In this case, the distances between trains are maintained on the basis of data on the speed of the rolling stock and an analysis of its braking distance. Based on this data transmitted by the system, a safe margin of separation between trains performing their transport tasks is calculated [3, 24, 58]. Data analysis takes place in the driver's cab using ETCS/ERTMS devices, where the situation on the tracks is presented, allowing the driver of the Euro locomotive to make a decision on how to proceed with the task. In accordance with the ETCS/ERTMS at implementation levels 2 and 3, as mentioned in the first chapter, traffic is controlled on the basis of decisions made by the driver based on information received through communication between on-board devices and trackside devices to the RBC. In addition, thanks to the support of the GSM-R communication system, it is possible to talk about mobile block sections. Figure 4 illustrates the methodology of mobile block signaling and the methods of implementing train runs traveling on a single track in one direction, one after another [4, 16, 17].

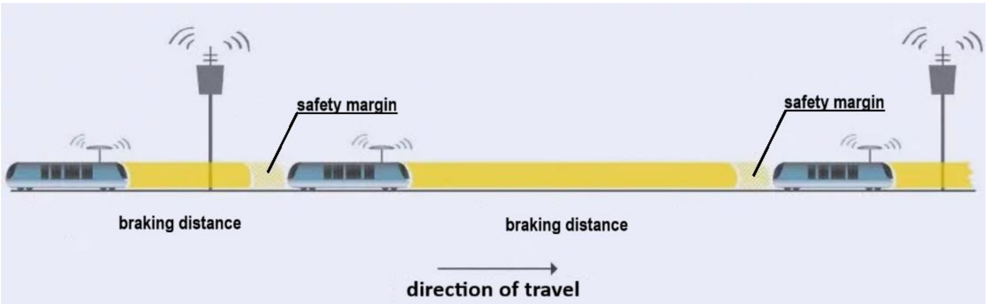

Figure 4. Diagram of the operation of fixed mobile block sections [23]

As can be seen in Figure 4, classic trackside signaling is not used for movable block sections, but rather signaling based on communication, which, thanks to the reception of signals from Euro locomotives and the specific nature of the data, can lengthen or shorten a given block section in order to ensure the safe execution of train runs [19, 30, 31]. They allow for an increase in the capacity of the railway line by increasing the frequency of transport tasks, as blocking of passage is based on an analysis of speed and braking distance. In addition, it is worth noting that thanks to the increased flow of information about transport tasks, they are performed in a safer manner, as the movement of rolling stock and its speed, on the basis of which the braking distance is determined, are constantly monitored [8, 11, 21, 58, 59]. This solution is fully in line with high-speed rail, which is why it works best on lines where passenger transport tasks are performed, in the case of which we can talk about fast, light, and short trains, then a significant increase in railway line capacity can be observed thanks to the reduction of distances between trains. In a situation where the line operates a mixed cycle, i.e., passenger and freight or freight only, the speeds achieved by trains are significantly lower and their lengths are significantly greater, which means that traffic moves more slowly. However, the introduction of mobile block sections on such lines also has its justification, as very long freight trains in standard line blocks can occupy two block sections at the same time, which significantly increases the distance [17, 25, 30] The use of movable block sections on such lines allows for a reduction in the distance between trains based on an analysis of speed and braking distance, thereby increasing the capacity of the railway line. Analyzing this application and the overall functioning of the idea of moving block intervals in the ETCS/ERTMS system and the architecture of this system, we can talk about a significant improvement in safety through the accurate flow of data on the situation on the railway line. The train is located using balises and information transmitted by radio using the GSM-R communication system. This makes the location of the train much more accurate than when using the standard method of determining the position of the train, which is wheel sensors used in standard systems [3, 4, 25, 31].

3 DETERMINING THE TIME TAKEN BY ROLLING STOCK TO TRAVEL ON A RAILWAY LINE WITHOUT AN ETCS/ERTMS SYSTEM AND WITH AN ETCS/ERTMS SYSTEM

One of the basic parameters affecting the capacity of a railway line is the time taken by rolling stock to cover the distance. It is worth noting, however, that this time depends on the configuration of the track system, as well as on the human factor, i.e. the work of traffic controllers and persons responsible for traffic management [19, 32].

In the case of a railway line that does not have an ETCS system in place, the time taken to complete the route can be expressed using formula (4) [8, 17]:

$$t^n = t_{pdp} + t_r + \frac{l_{zb}}{v_n} + \frac{(v_n - v_o)^2}{2 \times a_h \times v_n} + \frac{l_j + l_p}{v_o} + t_{rdp} \tag{4}$$

where:

t^n – travel time (s),

t_{pdp} – time needed to operate traffic control devices to prepare the route for the train (s),

t_r – time needed to cover the visibility distance, or the driver's reaction time (s),

l_{zb} – length of the approach distance, equal to the length of the block interval or the distance between the last block signal and the entry signal (m),
l_j – length of the route in the train route (m),
l_p – train length (m),
v_n – normal train speed (m/s),
v_o – limited train speed (m/s),
t_{rdp} – time of handling signaling devices during the train route solution (min),
a_h – train braking acceleration (m/s2).

$$t_{stETCS}^{n} = t_{pdpETCS} + t_r + \frac{l_{zb}}{v_n} + \frac{(v_n - v_o)^2}{2 \times a_h \times v_n} + \frac{l_j + l_p}{v_o} + t_{rdp} \quad (5)$$

where:
$t_{nst\ ETCS}$ – time taken for a train equipped with ETCS to pass through a station (s),
$t_{pdpETCS}$ – time needed to operate signaling and traffic control devices to prepare the train route or set the line block (including ETCS system devices) (s),
t_{rETCS} – time needed to transmit information to the driver's cab and for the driver to react to the information displayed on the console (s),
$t_{rdpETCS}$ – time needed to operate signaling devices when releasing the train route or releasing a line block (including ETCS system devices) (s).

4 SUMMARY

In recent years, the development of rail traffic control systems has become one of the most important elements of modernizing European railway lines. Many publications emphasize that traditional railway traffic control devices, even when modernized, have their inherent technical and organizational limitations. This is why the European ETCS/ERTMS system was introduced, which takes rail traffic management to a completely new level, enabling increased capacity, shorter travel times, and a reduction in potential human errors [1, 5, 6, 12]. In the scientific literature, including studies by the Warsaw University of Technology, the importance of ETCS for line capacity is a particularly frequent topic. The works of Professor Andrzej Kochan and researchers collaborating with the Railway Traffic Control Department at the Warsaw University of Technology emphasize that capacity is no longer solely a function of track systems but equally depends on the quality of the control system, its architecture, level of automation, and continuity of information transfer [30, 58, 59]. These authors point out that only the full implementation of ETCS Levels 2 and 3 allows the potential of the modern railway network to be fully exploited, minimizing the gaps between trains and increasing the reliability of the entire system. Numerous studies and reports also conclude that traditional national systems, used in parallel with ETCS, significantly limit interoperability. Only the transition to a uniform European system allows for free crossing of national borders without the need to change rolling stock or on-board equipment [17, 19, 23]. In their publications, Professor Kochan and colleagues emphasize that interoperability is a prerequisite for the development of international rail transport and a key argument for the full implementation of ERTMS in Poland [58, 59]. Technical analyses conducted by the Warsaw University of Technology also describe in detail the connections between GSM-R radio technology and the capabilities of the ETCS system. They emphasize that stable radio communication is the foundation for Levels 2 and 3, where data transmission replaces traditional semaphores and line devices [16]. These conclusions correspond well with previously published works on GSM-R [3, 4, 7, 31], which indicate the need for its continuous modernization to meet the growing demand for data throughput in rail traffic. PW studies also reiterate the theme of increasing traffic safety through the use of accurate algorithms supervising driver behavior and continuous monitoring of train position [58, 59]. The DMI interface and the automatic braking system appear as key elements that minimize the risk of human error, especially in conditions of intense traffic or poor visibility [11, 32]. These system elements are also extensively analyzed in TSI documents and UIC materials that describe traffic management standards in Europe [19, 21, 24]. Regarding the impact of ETCS on throughput, PW publications highlight specific mechanisms – shortening block headways, smoother speed regulation, and eliminating unnecessary stops resulting from imprecise traffic management [25, 58]. This thesis is also confirmed by analyses of European institutions, which in their reports clearly indicate the possibility of increasing the number of trains on a line by several to several dozen percent, depending on the adopted system level and infrastructure specificity [22, 23]. Advanced level 3, often discussed in research literature, especially in the context of the future of European railways, is considered the target point for system development. Thanks to full radio communication and uninterrupted information on train integrity, it enables more dynamic traffic management, without fixed physical block spacing [16, 20, 22]. Professor Kochan and co-authors indicate that although level 3 is not yet widely implemented, it will be a key element in increasing capacity on the most intensively used main lines in the future, also in Poland [59] In summary, the analysis performed in this paper and presented in the literature – especially in publications of the Warsaw University of Technology – confirms that the introduction of ETCS/ERTMS has a real impact on the increase in capacity and safety of railway traffic. The unification of the control system, the strengthening of radio communication, the standardization of traffic management procedures and the possibility of automatic train control create a coherent, modern system that responds to the needs of the developing transport in the European Union [17, 19, 23, 58, 59]. In this understanding, the aim of the work was fully achieved – both technical and functional benefits resulting from the implementation of ERTMS were demonstrated, and the prospects for the development of the system in Poland and Europe were presented.

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