Journal of civil engineering and transport **transEngin**

2023, Volume **5** Number **2** **ISSN 2658-1698, e-ISSN 2658-2120**

DOI: 10.24136/tren.2023.008

DISTURBANCE OF TRAINS MOVEMENT UNDER THE ERTMS CONTROL SYSTEM

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Reviewed positively: 8.12.2022

Information about quoting an article:
Sumiła M. (2023). Disturbance Of Trains Movement Under The ERTMS Control System. Journal of civil engineering and transport. 5(2), 49-60, ISSN 2658-1698, e-ISSN 2658-2120, DOI: 10.24136/tren.2023.008

Abstract – The article presents a discussion leading to the identification the possible causes of disturbances in train movements under the supervision of the European Rail Traffic Management System ERTMS. As a consequence of detected events, unintentional initiation of a train braking procedure occurs despite the absence of objective reasons for such behaviour. In essence, the paper presents the ERTMS as a real-time system based on the two subsystems ETCS and GSM-R. Each of these subsystems includes a vehicle part and an infrastructure part. The article starts by identifying general considerations that may affect the lack of compatibility between vehicle and trackside infrastructure as a result of changes in versions of the specification (baseline). The following part of the article reviews the process leading to train braking is reviewed. The next part of the article refers to ETCS scenarios and parameters affecting the system response during operation. It referred to the considerations of message transmission between the ETCS ground infrastructure and the vehicle via the telecommunications network, including the GSM-R. The final section focuses on the causes and consequence of the overlap of the RBC's and GSM-R radio cells boundaries. The article concludes with a brief summary and conclusions.

Key words – disturbances, ERTMS, Real-Time Systems, QoS

JEL Classification – L92

INTRODUCTION

The aim of the originators of Trans-European rail system was to create the conditions which enable moving trains between the countries of the European Union without unnecessary disturbances. These conditions are presented in the form of several unified Technical Specifications for the Interoperability of the railway system, so-called TSIs. Issued specifications allow to build interoperable / compatible vehicles and the infrastructure in the European Union (EU) and simplify operational process of trains at the borders. Undertaken actions initiated throughout the EU, with the use of huge resources, were aimed at adapting existing railway infrastructure and of course the new one to enable the Trans-European transport channels for interoperable trains.

Poland is the country where the decision on the commercial use of the ERTMS/ETCS Level 2 was taken relatively late. A pilot of commercial run was launched on a part of the E-65 corridor (Warsaw – Gdańsk) in December 2020. The line adaptation to ERTMS standards has been ongoing since 2011. The first years of the pilot operation of the ETCS Level 2 has provided experience and has shown problems in continuity of maintaining the vehicles' supervision moves under the ETCS system. As a result, the safety procedures are triggered in some trains by ETCS on-board units which results in unnecessary braking.

The literature review related to ERTMS implementation issues is extensive and covers a wide spectrum of issues starting from development of the formal methods for signalling and interlocking systems [2-3, 11], through the issues related to the automatic protection systems [23], safety problems [9], risk assessment [4, 17], ERTMS capacity [14], communication [12], challenges connected with introduction of ETCS Level 3 [10] and finally the implementation problems [13]. Despite so many publications available from the scientific world, there are no known studies that can serve as sources providing a basis for the further analysis presented in this article, other than documents of the manufacturers of ERTMS equipment and issued by ERA.

The following part of this article draws attention to the overlooked challenges of implementation the ERTMS and the problems of maintaining traffic continuity for trains moving under the supervision of the ETCS Level 2.

1. ETCS AS A REAL-TIME SYSTEM

In search for answers to the causes of abnormal trains' movement, it is necessary to define the main way of how ETCS system works. In that sense the ETCS is a distributed real-time control system dedicated for trains' control. It includes equipment belonging to a track-side infrastructure and equipment installed on trains. In consequence, the ETCS system is divided into two subsystems: the on-board subsystem and the trackside subsystem. The environment of ERTMS/ ETCS system is composed of:

- the train, which will then be considered in the train interface specification;
- the driver, which will then be considered via the driver interface specification;
- other on-board interfaces (full list of interfaces is described in SUBSET-026 [21];
- external trackside systems (interlockings, control centres, etc.) for which no interoperability requirement will be established.

The defined ETCS data flow is given in the ETCS SRS 3.6.0 SUBSET 26 [21]. It includes the interaction in the chain of relationships shown in Figure 1.

To control train movement under the ERTMS/ETCS based system, the ERTMS/ETCS on-board equipment is needed to establish communication and exchange information between the track-side subsystem and on-board subsystem to locate the train on track and to set conditions for its' movement. The following information shall be given from the track-side:

- permission and distance to move as a Movement Authority (MA);
- when a limitation is needed i.e. Mode profile for On Sight, Limited Supervision or Shunting and Signalling related speed restriction, the Mode profile and Signalling related Speed restriction shall always be sent together with the MA to which the information belongs;
- track description covering the whole distance defined by the MA;
- linking information when available.

As it is shows on Figure 1 the exchange of information between trackside interlocking subsystem via RBC to on-board subsystem via OBU, the EuroRadio protocol uses to bearer services and GSM-R network. The data bearer services are described as data access and transfer in the GSM-R network from the MT, a network gateway and the interworking with ISDN or IP networks to the Terminal equipment on the infrastructure side. More detail description in section 5.

It is important that the entire communication process takes place within a set of time which is shorter than the sum of the unit handling times of the individual tasks involved in the message exchange. The time of message transmission may vary in different modes. The time of the MA message transmission is more predictable and depends on its length (number of bits including extra bits of HDLC named octets in this protocol) and the baud rate (bit per second). The MA message length is between 250 to 750 octets. The transmission rate is defined from 1.2 kbps to 9.6 kbps, typically is establish 4.8 kbps. The worst-case value takes into account all normal perturbations GSM-R cell Handover but excludes more serious effects such as burst errors due to electrical interference or loss of communication. Hence, the normal case mean transmission time would be 4.5 s for 250 octets MA with a normal case maximum update time of 12.5 s with 750 octets MA. This leads to the conclusion that the MA update allowance of maximum 12.5 s would ensure that all MA updates occur without operational delay (excluding effects of interference bursts and loss of communication).

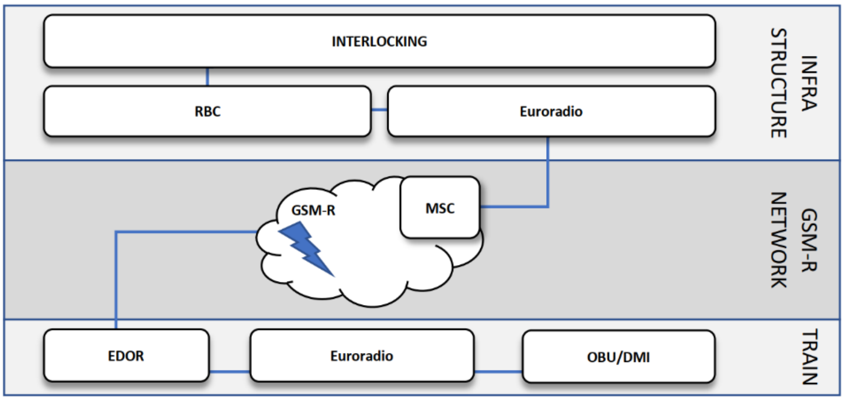

Fig. 1. Simplified ETCS communication block diagram (based on SUBSET-026, p. 2.5.3, Fig. 1 [21])

In PS mode, as it shows Figure 2, the IP network is involved in transmission chain which introduces additional uncertainty in the estimation of the message delivery time.

In general, the end-to-end delay operational process of the MA transfer and processing time t_{Total} means the total time of delay between the interface of interlocking and RBC and the interface between ETCS on-board unit and the driver. The time for the trackside, the GSM-R part and the ETCS on-board unit include the following parameters:

- ETCS data length (t_1);
- data transmission from interlocking to RBC (t_2);
- RBC + Euroradio delay (t_3) including (e.g. HDLC procedure in case of transmission interference);
- data transmission from RBC to mobile network, including commutation process in PBX ISDN network (t_4), data transmission via optical core network and any necessary data retransmission due to GSM-R cell handover process (t_5);
- ETCS Data Only Radio behaviour (t_6);
- signal processing time of ETCS on-board including Euroradio and DMI update time (t_7);
- estimated breaking time (t_8).

In summary, the ETCS is a real-time system in which processes must be completed within a set time. Exceeding the permissible time t_{Total} leads to the implementation of emergency procedures.

$$\sum_{i=1}^{8} t_i \le t_{Total} \tag{1}$$

The Figure 2 illustrates the operational process with the division of time into different tasks.

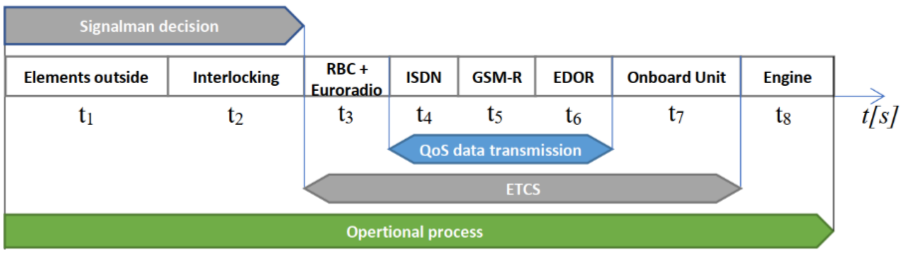

Fig. 2. Timeshare of ETCS and data-transmission of the operational process (based on [19] Fig. 1)

Great number of the listed parameters are predicted or can be assumed for a given infrastructure. The values of these parameters are determined during the construction phase of the ETCS and GSM-R infrastructure or are defined by the technical specifications. The measurable time of reaction often depend on used technology in the infrastructure. Longer delays than assumed are the result of a part of the signalling chain failure. Some of the ETCS CCT subsystem parameters come from the nature of internal process and they are difficult to define with absolute certainty. The uncertainty expressed in statistical distribution is also connected with the radio transmission aspects between track-to-train and train-to-track subsystems.

2. Preliminary Analysis

The phenomenon of the activation of unintentional train braking process introduced at the beginning of the article was observed for certain types of vehicles. In addition, it was found that these events always occur at the same locations on the railway line. This leads to first suspicions. The cause of disturbances might be connected with:

1. vehicle – running on an interoperable railway line is not fully compatible with the infrastructure, or
2. location – where the incidents of loss of control over the train typically occur.

Although the first of the identified reasons of the train movement disturbance should not have appeared for the interoperable trains, we should consider additional two important indications:

1. The specifications CCS TSI, despite being the cornerstone of interoperability of the EU rail system, has changed several times since it was first published 1999. The current standard of TSI CCS [5, 6] has been developed into a version of BASELINE 3.6.0 [21] in 2016. The trackside ETCS signalling infrastructure of considered E-65 corridor was designed, built and authorised at the end of the investment process according to earlier i.e. 2.3.0 TSI CCS specifications. Nowadays trains, certificated according to the BASELINE 3.6.0, are not fully compatible with the trackside subsystem in E-65 corridor.
2. The each part of TSI specifications are divided into three main groups: MI - Mandatory for Interoperability, M - Mandatory and O - Optional.

The first of these specifications is strictly necessary to meet the essential requirements for the interoperability of the rail system. The second group is equally important. It describes many vital features and functionalities of the system but a full implementation of all the M specifications is not necessary to achieve the essential functionality of the interoperability of the system. Therefore the European Commission has not made it compulsory to implement all the M specifications in the CCS subsystems, so as not to impose unnecessary high costs on contracting authorities in terms of investment to bring the rail system into line with interoperability requirements. Giving up part of the M requirements leads to incomplete functionality of parts of the CCT and CCO [6] of subsystems and that might possibly lead to disturbances in train operation. The last group, like the previously discussed, is at the discretion of the contracting authority.

First conclusions. The development of the technical specifications of the TSI CCS has led to changes that could potentially lead to incomplete compatibility of the track-side and the on-board control-command subsystems. The conduct of such tests was included in the latest issue of the TSI CCS [6] in clause 4.2.17 and is described in the ESC and RSC test scenarios. Nevertheless, the empirically verification can be performed by checking:

1. comparison different types of vehicles with the same BASELINE and
2. comparison the same BASELINE versions on different trains but comes from the different CCO manufactures.

If both checking give positive answers, it means that the cause of the interference lies somewhere else. The second suspicion of the undertaken preliminary analysis is focused on the locations where the train CCS system has disturbances. The case will be considered in the following paragraphs.

3. ANALYSIS OF BREAKING PROCESS

A sequence of events that leads to an abnormal train breaking is a consequence of the loss of communication detected by the Quality of Service mechanism. The mechanism is implemented inside the different layers from the ETCS application layer, through the Euroradio protocol stack to the GSM-R network. Loss of communication at the lower layers, i.e. in the Euroradio layer and the GSM-R network, between updates moments at ETCS layer, will not cause perturbations in train movements. A description the QoS mechanism of ETCS can be found in the test specification documents: SUBSET-093 [22], O-2475 [16] and also in EEIG:04E117 [19].

The loss of communication detected by at the ETCS application layer is based on timeout the T_NVCONTACT counter receiving MA message. The counter indicates the maximum waiting time for a 'safe' message. The description of this message given in the ETCS SRS SUBSET-026-7 p.7.5.1.148 gives: “If no 'safe' message has been received from the track for more than T_NVCONTACT seconds, an appropriate action according to M_NVCONTACT must be triggered” [21]. The maximum waiting time for such a message is user-defined and varies from 0 to 254 seconds. The value of T_NVCONTACT is often based on national safety considerations. The counter setup equal 255 means for the system infinite time. The value for the duration of the entire operational process is set individually by each infrastructure manager and is based on national safety considerations. The different railways propose very different values for this parameter. For example [22]:

- Spain: 6 s for high-speed lines, 10 s for conventional lines;
- Netherlands: 40 s to 60 s;
- Italy: 7 s (based on the values of the previous generation system BACC (It. Blocco Automatico Correnti Codificate));
- France: 9 s (based on the values of the previous generation system TVM (fr. Transmission Voie-Machine));
- Poland: 20 s for each ETCS line;
- Germany: 40 s (adopted based on LZB (ger. Linien Zugbeeinflussung) system values);
- United Kingdom: standard 80 s (based on the assumption that crossing one faulty BTS has no effect), or 255 (infinity) for railway lines with large radio holes.

Exceeding the accepted half of the time T_NVCONTACT for receiving a new MA message aware a driver of the need to apply the brake to stop the train before the end of the current MA and when the on-board system do not receive a new MA until the T_NVCONTACT timer expire. In such condition the driver will apply the brake to stop the train.

During the time the ETCS application layer waiting for a new MA message the Euroradio layer attempts to re-establish the connection with the RBC via the GSM-R network. This process is unavoidable due to the movement of the train, the change in the RBC affiliation, and the HO between BTS sites in the GSM-R network. The Euroradio layer will make a maximum of three reconnection attempts. The impact of the failure will depend on the conditions prevailing at the time the loss of communication was detected.

If the train has just received an MA, it has no impact on the train movement. If the train is about to receive a new MA and is approaching the braking area of the braking curve, the braking procedure is activated. The process can be illustrated as it was presented in figure 3.

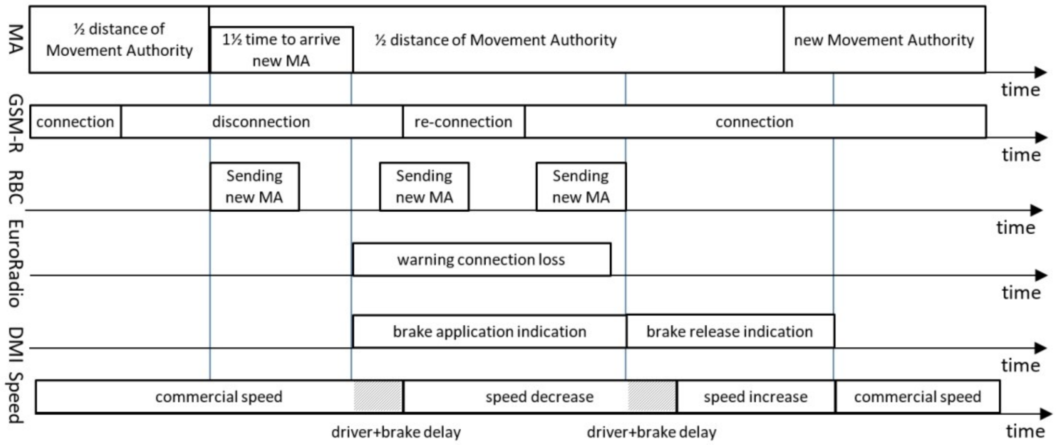

Fig. 3. The sequence of events triggered after detection of a loss of connection with the ultimate aim of re-establishing the connection between the on-board and the RBC (based on Fig. 19 [19])

Finally, the communication network shall be able to support transparent train-to-trackside and trackside-to-train data transfer at the speed of 500 km/h e.g. in tunnels, cuttings, on elevated structures, at gradients, on bridges and stations. The network shall provide a Quality of Service for the ETCS data transfer and shall not depended on network load.

4. TRACKSIDE INFRASTRUCTURE ANALYSIS

The CCT subsystem base on a network of build-in infrastructure devices communicating and interacting with vehicle in real-time conditions. The main functional blocks belonging to the trackside infrastructure are shown in Figure 1. Parameters t_1, t_2, t_3 on Figure 2 represent the time budget required for the trackside signalling subsystem to keep the train running. The parameters t4 and t5 are also part of the trackside infrastructure, but relate to the telecommunications subsystem, which will be discussed in Section 5.

Typical driving scenarios under ETCS and relevant QoS parameters with application rules are gathered in Table 1.

Table 1. Scenarios & **Relevant Parameters** (source Tab.7 [19])

	Scenario	QoS Parameters	Application Rules
1	MA extension	- Transfer delay; - Transmission error rate;	- Short MA for time critical scenarios
2	Entry into Level 2	- Registration delay; - Connection establishment delay; - Connection establishment error rate; - Transfer delay; - Transmission error rate;	- Radio coverage - Balise group locations
3	Awakening / Start of Mission	- Connection establishment delay; - Connection establishment error rate; - Transfer delay;	
4	RBC/RBC handover	- Connection establishment delay; - Connection establishment error rate; - Transfer delay; - Transmission error rate;	- Balise group locations
5	Communication loss / T_NVCONTACT	- Registration delay; - Connection loss rate; - Connection establishment delay; - Connection establishment error rate; - Transfer delay; - Transmission error rate;	- Radio coverage - Number of mobile stations on-board - Short MA for time critical scenarios

The scenarios indicates to the different cases where the continuity of a train movement can be disrupted and do not refer to the different modes of running under the ETCS control. The parameters listed in the third column are related to the execution time of a given activity in the process performed by the ERTMS system. Exceeding set response time limits of system elements is treated by the ETCS system as a failure and leads to the triggering of train safety procedures.

While the train is running and on-board devices are registered, establishing a new connection to the RBC should be accomplished within 10 s. Transmission errors may occur during this time, but should not be longer than 1 s. Hence the QoS of data transmission gives

$$t_4 + t_5 + t_6 \leq 11 \text{ s} \quad (2)$$

Additional analysis and tests indicated in [19] shows that in normal conditions MA message takes up to 7 s to be generated without any extra time introduced by the RBC component. The RBC processing time normally take up to 2 s and it needs to take into account the additional margin for burst errors (min. 3 s). For this reason values of T_NVCONTACT less than 12 s are likely to result in unexpected interference in the normal ETCS data transmission process.

$$\text{T\_NVCONTACT} = t_{Total} > 12 \text{ s} \quad (3)$$

In addition, SUBSET-093 p. 6.6.3.3 [22] gives the infrastructure managers some extra clues in order to expand the time in the timer T_NVCONTACT to value ≥38.5 s. For rational reasons the timer should oscillated at least around 40 s and should be a part of the National Values. The Polish railway manager assumes, as it was mentioned above, the value of 20 s, which is acceptable corresponding to assumption in equation 2.

5. Communication analysis

The end-to-end bearer communication service can use CS mode or PS mode. The choice of mode affects the transmission time over the network and the probability of internal fluctuations. Figure 4 shows the path used to direct a message between the OBU and RBC in each of the communication modes. In case of use CS mode the end-to-end QoS requirements are specified between the interface $I_{GSM\text{-}R}$ at the service access point and the interface $I_{FIX\text{-}CS}$ at the RBC side. The end-to-end QoS requirements for PS mode are specified between the interface I_{GPRS} at the service access point and the interface $I_{FIX\text{-}PS}$ at the RBC side. Other QoS requirements are applicable to the interface I_{GPRS} and the network interface at reference point G_i according to [22].

Generally, delays in the ICT networks are based on probability processes and they are widely described in telecom literature.

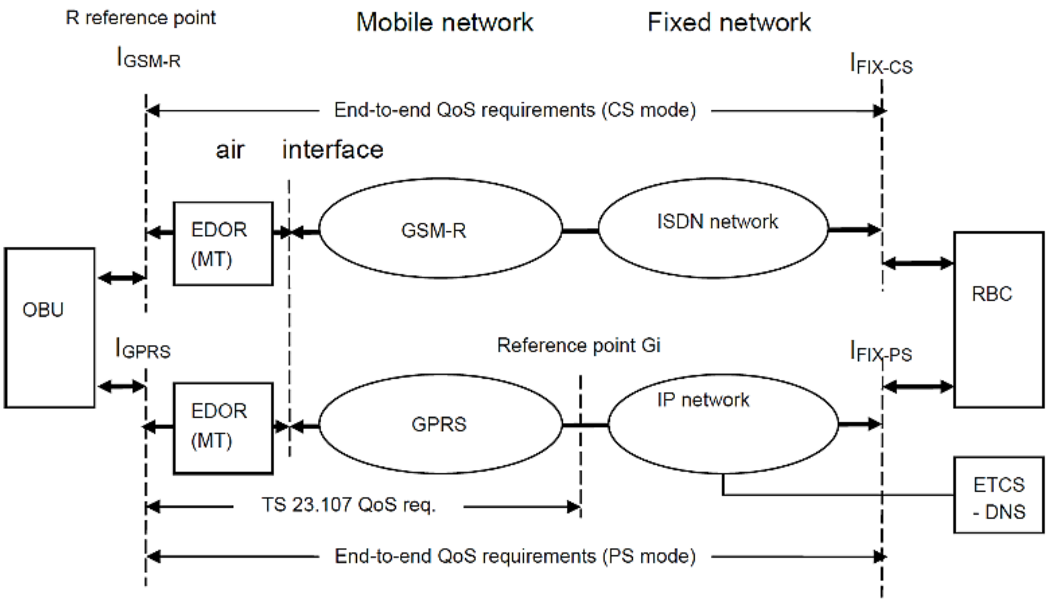

Fig. 4. The end-to-end data bearer services (based on [22] Fig. 1)

The cause of delays or loss of communication in the GSM-R network layer can be result of [27]:

- connection establishment delay;
- connection establishment error ratio;
- connection loss rate;
- network transfer delay of user data frame;
- data transmission interference;
- GSM-R network registration delay.

The list of cases are connected to communication delays and are the consequence of non-confirmation of one or more indicators describing communication in the GSM-R network. According to the description and Figure 4, different interfaces and the network modules are used for CS and PS modes. Their influence on the parameters needs to be taken into account. For example in CS mode it need to pay attention to the following parameters:

1. The operational QoS targets of [19, table 6] are required, then the ETCS infrastructure including the GSM-R network has to be designed in such a way that at least two consecutive connection establishment attempts will be possible (Recommended pre-condition for ETCS infrastructure);
2. Connection Establishment Delay is defined as the value of elapsed time between the connection establishment request and the indication of successful connection establishment. Mobile originated calls shall be ≤10 s (99 %). If data is not exchanged in a longer period of time after receiving connection establishment indication CONNECT, the attempt shall be evaluated by the ETCS application as not successful. To trigger the second connection establishment, delays >10 s will be evaluated as not successful and the connection process of the first attempt will be cancelled by the on-board communication system. It is assumed that an unsuccessful connection establishment will cause train operation delays of less than 5 min.
   A complex derivation from table 6 [19] and the following text suggests that a value $<10^{-4}$ is acceptable for entry into ETCS L2/L3.
3. Connection Loss Rate is defined as a number of connections released unintentionally per accumulated connection time and shall be $\leq 10^{-2}$ per hour. The operational QoS-targets of the ETCS infrastructure has to be designed in such a way that at least the following conditions are fulfilled (Recommended pre-condition for ETCS infrastructure):
   - T_NVCONTACT ≥ 38.5 s and
   - M_NVCONTACT different to train trip and
   - A new MA reaches the OBU before standstill.

   The connection loss influences MA propagation time. As it was stated in [19] chapter 7 the ETCS message delay caused by connection loss indication and re-establish of the ETCS safe connection. It shall take at least 22 s and it is extra time for the MA transfer delay. In case of a connection loss, the operational targets to MA extension should not excide 12 s and can never be fulfilled. Finally, the loss of connection has influence on the increase of probability of trains delay.
4. End-to-end Transfer Delay of a user data block is defined as the delay between the delivery of the first bit of the user data block at the service access point of the transmitting entity and the reception of the last bit of the same user data block at the service access point of the receiving entity. The end-to-end Transfer Delay of user data block of 28 octets shall be ≤0.5 s (99%) but if the connection loss occurs additional delay of 5 s has to be taken into account.
5. MA Transmission Violation Rate is defined as a number of MA Transmission Violations during the measurement time. MA Transmission Violation occurs when sent the MA message consisting of 250 octets is not received within 12 s. MA message is transmitted every 20 s. If MA message or its parts are erroneous, the time of retransmission should take 7 s without additional transmission disruptions. MA Transmission Violation Rate shall be $\leq 10^{-2}$ per hour.
6. GSM-R Network Registration Delay is defined as the value of elapsed time from the request of registration to the indication of a successful registration. The network registration has to be successful before reaching the announcement balise. If there is no registration passing this balise, the ETCS application will not try to connect the RBC. In this case the train will be stopped at the border to the L2/L3 area. The Network Registration Delay shall be ≤35 s (99%), since the parameter >40 s is evaluated by the ETCS application as not successful. A commonly used value for this target value is 40 s (see [19]), but can differ according to national definition.

The accepted times for the effectiveness of GSM-R including ISDN system are defined in the p. 6 of SUBSET-093 specifications [22]. A loss of communication detected by the GSM-R equipment i.e. EDOR may be caused by one of the following circumstances:

1. Failure of the last active EDOR on the train;
2. BTS of GSM-R radio network failure;

3. Delay during transmission of messages through the network;
4. Lack of EDOR receiver resistance to strong interfering signals from public broadband networks operating in 900 MHz band – the problem is discussed in the works [7, 8];
5. Lack of free radio channels to handle a new call (radio cell overload) – the problem is discussed in the other Author's works.

The listed causes of interruption connected with the radio communication layer should be treated as well-known phenomena in the theory of telecommunications systems. In principle, their occurrence should be regarded as accidental phenomena; nevertheless, in GSM-R railway radio communication networks, they need to be reinterpreted.

The failure of an active EDOR radio in the OBU train's unit is related to the environmental conditions of device working (vibrations, lack of ventilation, wide range of temperature), prolonged periods of use (sometimes up to 24/7) and the natural process of ageing of the device. EDOR devices are designed for mentioned operating conditions (manufacturers declare MTBFs of >10,000 h), nevertheless failures happen. In concern for such a threat the current CCS TSI [6] require installing at least two EDOR modems to handle the on-board ETCS equipment in a train. As a result, the availability rates for the EDOR modems in the on-board ETCS equipment increased, because the event of failure of one from two or more modems do not lead to interruption of the train movement.

The failure of a local BTS is related to the failure of a network infrastructure element and is not directly related to the vehicle. The infrastructure designed by GSM-R network providers meets high requirements in terms of network reliability and availability. The GSM-R network built in Poland has redundancy in the sense of double radio coverage layers for ETCS lines. In consequence, the failure of a single BTS will not lead to the loss of the GSM-R radio signal in a given area, because the coverage will still be available from alternative BTS transmitters of the second network layer.

The third cause of interference in the radio communication layer concerns the operation of the network layer. Transmission delays can be influenced by a number of reasons among which CS and PS switching modes, fibre backbone network failures, Handover time, NSS congestion and many others. The maintenance of appropriate network performance indicators lies on the side of the GSM-R Network Management Centre of the national network operator.

Lack of EDOR receiver resistance to the strong interference signals from public broadband networks operating in 900 MHz band has been noted since 2007. The experience of western European countries after implementation the 3G and 4 GSM networks shows that the public transmitters can cause radio interferences and have influence on the operation of receivers of GSM-R system. The issues related to the coexistence of GSM-R and MFCN networks elaborate the UIC, the European Railway Agency (ERA), as well as a CEPT committee the ECC (Electronic Communications Committee). The CEPT ECC Committee reports [7-8] explains and show the scale of the phenomenon and its consequences within the work of the GSM-R system and its terminals. The problem of the GSM-R signal interference is not easy to solve [8] and mitigation actions such as proposed in [26] allows to improve stability of communication with the on-board units on the train. Report 229 [8] indicates the need for close cooperation and action on the part of both the GSM-R operator and the public mobile network operator whose transmitters are the source of interference.

The last of the causes identified in this section is related to poorly designed radio networks. The problem particularly affects networks built on GSM 2G technology and for a small number of radio channels available in the cell. GSM-R is embedded in the 900 MHz band and operates on 19 radio channels with a width of 200 kHz. Each radio channel provides 7 time slots for communication in TDMA mode or 13 slots for two channels, which seems to give quite a large number of slots for communication. Nevertheless, as the author has shown in previous publications, the number of channels available for communication may not be sufficient, as each train in the radio cell area with active ETCS L2 equipment may occupy up to 4 radio channels, the range of a typical radio cell in a GSM-R network is 7 to 12 km means that a shortage of network resources is likely to occur already for the fourth train in the radio area. In addition, cellular network planning rules dictate that the pool of available 19 radio channels should be managed quite carefully to avoid repetition and overlap of nearby channels.

The last of the causes identified in this section is related to poorly designed radio networks. The problem particularly affects networks built on GSM 2G technology and wrong divided areas of the railway network according to the small number of radio channels available. GSM-R as a cellular system base on GSM 2G technology and operates on 19 narrowband radio channels in the 900 MHz UIC band. Each radio channel provides 7 time slots for communication in TDMA mode or 13 slots for two 200 kHz radio channels, which seems to give quite a large number of slots for communication. Nevertheless, as the author has shown in previous publications, the number of channels available for communication may not be sufficient for large the radio cells where trains operate under ETCS L2 system. In such circumstances the on-board radios (EDOR, Cab Radio and handhelds) may occupy up to 4 radio slots which leads to a situation where there may be a shortage of network resources. For a typical radio cell in a GSM-R network (7 to 12 km) it means that for one radio channel the problem occurs for the fourth and more trains in the radio area. In addition, cellular network planning rules dictate that the pool of available 19 radio channels should be managed quite carefully to avoid repetition and overlap of nearby channels.

In conclusion, it should be noted that the occurrence of train disturbances due to causes 1, 2 and 3 should be considered as rare and not systematic for a well-planned network. Disturbances of the train moving occurring due to radio interference have been extensively described by the author in previous publications and can be regarded as a guideline for looking for reasons of lack of communication between on-board equipment and trackside infrastructure. Depending on the strength of the interference signals, the communication problem may occur on most or only some types of trains. The usage of the proper radio filters and newer types of EDOR modems can mitigate the susceptibility of the on-board ETCS instance to communication interference. Cases of trains that regularly initiate emergency braking at a particular location may therefore indicate the need for closer verification of the on-board equipment of this type of train. The last mentioned case may concern a random group of vehicles whose appearance in the area of a radio congested cell does not allow them to continue to run under the supervision of the ETCS equipment. In such case, the circumstances and locations where the loss of communication occurs deserve attention. It is expected that communication with the network is lost when entering the area of a new radio cell and that equipment cannot log on when attempting to activate the ETCS system on a vehicle in a sensitive radio cell. The responsibility for confirming this type of interference lies with the network operator itself, as only it has the tools and access to the statistical data to make an absolute diagnosis of such interference in the GSM-R network.

6. CORRELATION OF ETCS AND GSM-R SYSTEMS

The investigation carried out in the previous sections could be considered incomplete, as it discusses each of the areas affecting train disruption independently. In this section, the case of the cumulation of adverse disruption causes comes from the ETCS and GSM-R subsystems as a result of overlapping critical conditions for each subsystem will be discussed.

The case discussed here may arise under conditions where the designers of the GSM-R network and of the ETCS control system have not established cooperation at a sufficiently early stage of design and area planning of their systems. The lack of coordination under the conditions of parallel work on the implementation of GSM-R and ETCS in the same area is particularly dangerous when the area for responsibility of the ETCS system was not clearly defined before the radio network was planned. Lack of cooperation between the GSM-R network contractor or, later on, the operator and the ETCS infrastructure contractor can lead to overlapping of critical sites for both systems and lead to disturbances that are difficult to correct.

Based on the knowledge gathered in previous sections, three cases should be considered:

1. the direct overlap of the boundaries of GSM-R cell areas and RBC responsibility areas;
2. occurrence of a change of radio cell area at the locations where half of the MA section is crossed;
3. exceedance of the allowable message receipt time defined by the T_NVCONTACT parameter.

Table 1 indicates as a one of scenario Handover between adjacent consecutive RBCs' areas of responsibility is indicated as one of the scenarios. This process is important for safety reasons. In the process of designing the ETCS system on a given line, the engineers indicate the locations of the balises, whose task is to transmit this information to the on-board CCO system well in advance. Following reception of this information by the CCO subsystem, the ETCS on-board equipment establishes a new connection to the RBC into which it enters. It happens in the time before leaving the area controlled by the current RBC. If the announce balises have been placed in the correct places, the train can move at the maximum commercial speed. It can therefore pass smoothly under the control of the new RBC while maintaining its existing running parameters. Thus, a precondition for a smooth HO is that the announcement balises are placed well in advance and that information about the train entering the new RBC can be transmitted. The information obtained from the balises is used by the on-board ETCS equipment to establish a new connection to the RBC. This is performed via the GSM-R system. When the communication process via GSM-R occurs without interrupting the train, after receiving confirmation from the new RBC and the new MA, may continue running. If it does not receive a confirmation from the RBC, it can only move up to the boundary defined by the last MA received. Of course, during this time the on-board ETCS equipment reattempts the new MA, where at the same time initiates the braking process sufficiently in advance. In the scenario described here, the need to transmit a message from the train to the new RBC and to obtain a new MA is clearly indicated. However, the exchange of messages between the on-board equipment and the ground ETCS infrastructure can be disrupted when the Handover area between RBC-RBC overlaps with the Handover area of the radio cells in the GSM-R network. For CS mode, the process of establishing a new call requires terminating the current call and initiating and setting up a new call, similar to initiating a voice call. The time taken to set up such a call is determined by the specifications and is <8.5 s for 95 % of cases or ≤10 s for 100 % of cases. The values indicate that the time is long enough to at least initiate the train braking process by the on-board ETCS equipment at the limit of RBC responsibility until a new MA is received.

The second case discussed concerns the initiation of radio Handover in the middle of the MA section. In this case, there is no change of control area and no change of RBC, but the transition between radio cells is not precisely defined and occurs with some probability based on the analysis of the values of the received radio signal levels from the available BTSs and the algorithm implemented in the EDOR radio modem. A case can occur when a new MA is not transmitted after half the validity of the current MA, after more than 1.5 time the transmission time of the message containing the new MA. This is in accordance with the specification and description outlined in Section 3. As required the connection loss rate shall be $<10^{-2}$ /h. There after the on-board CCO subsystem will also initiate a safe braking process of the train until a new MA is received.

The third case refers to the wrong value of the T_NVCONTACT counter adopted by the infrastructure manager. As previously shown, this indicator should not be less than 12 s. Reducing this time below the indicated value may lead to random occurrence of exceeding of this timer and initiation of a train safe braking process. In some applications of the ETCS system with railway managers in EU countries, cases of abnormal system response have been recorded also for longer times of the T_NVCONTACT timer. Section 4 indicates that for the time longer than 7 s the probability of data transmission errors increases. In addition, only three calls to the RBC are initiated by the EURORADIO layer. In order to avoid accidental violations of the T_NVCONTACT, SUBSET-093 recommends extending this rate to approximately 40 s (the current release indicates a value of 38.5 s [22]).

In summary, the three cases described above are all directly related to the CCT subsystem. As a consequence, the train's safe braking systems may be triggered. The availability of only one active EDOR modem while the train is running increases the probability of running interruption. The case applies mainly to vehicles certified before 2016. Earlier releases of the CCS TSI did not mandate the installation of two EDOR modems in the CCO subsystem. In addition, earlier issues of the CCS TSI also did not allow EDOR operation in PS mode, which allows more flexible use of radio resources than the CS mode. Both changes were introduced after first Railway Undertaken experiences with using ERTMS system. It has been observed that the use of two active EDOR modems on a train provides the possibility to simultaneously log on to two radio areas when the train passes the boundary of the two radio areas' coverage, and therefore a smoother transition between them. When a train uses only one active EDOR modem, a vehicle moving with a high speed may not be able to establish a new connection to the RBC in a new cell in time, leading to safety procedures being triggered by the on-board CCO system. In addition, if the connection is dragged out until the single EDOR modem logs off, the re-logging time to the GSM-R network shall be ≤30 s for 95 % of cases or ≤35 s for 99 % of cases. Such a long time will be undoubtedly detected as non-communication state by the ETCS layer of the CCO subsystem on the train.

Finally, the problem of radio cell capacity in GSM-R should also be mentioned. The capacity is defined by the specifications of the GSM-R standard [25-26] inherited by GSM-R from the specifications of the GSM 2G public communication standard. This problem has already been discussed by the author in another publication and will not be discussed further here.

CONCLUSIONS

The ERTMS as the Control-Command and Signalling subsystem is a proven system in many European countries. The system is not perfect and can lead to unintentional train braking process as it shown at the introduction. The aim of the article was to emphasise the importance of time aspects in the control process. As shown, the ERTMS system belongs to the group of real-time systems. These type of systems are sensitive to the execution of tasks within an imposed time limit. Exceeding the time limit for particular task is perceived by the system as a failure, just as a failure of one of the system components for other non-RT systems. Regarding to this feature of the ERTMS system the problem of unintentional train braking process was considering. The decomposition of the problem analysis was divided into two main subsystems ETCS and GSM-R. Each of them was treated as an independent real-time system and such an analysis was carried out in the following section. The basis for the analysis was to trace the processes over the time and events which happen before and during the train braking process. For this purpose, scenarios relevant during the operation of the ETCS subsystem and the GSM-R subsystem were considered. As a result of the analysis, it was identified which processes have an impact on train running delays. Finally, Chapter 6 discusses the problem of the lack of coordination between the ETCS and GSM-R subsystems and possible future consequences.

The spectrum of aspects and conditions affecting the train movement under the control of real-time system leads to conclusion that the analysis of the causes of train disruption is a complex process and often requires individual treatment for each of the instances reported. At the end it should be remembered that the main feature of the ERTMS system is to keep safety process. The automation of signalling processes implemented in the ETCS system have to be sensitive to any sign of a safety hazard. One of the consequences of this approach to action is the activation of the train braking process in the absence of the required conditions to movement continue.

ABBREVIATIONS

1. **BTS** - Base Transceiver Station;
2. **CCO** - on-board Control-Command and signalling;
3. **CCS** - Control-Command and Signalling subsystem;
4. **CCT** - Trackside Control-Command and signalling;
5. **CS mode** - Circuit Switching mode;
6. **DMI** - Driver-Machine Interface;
7. **EDOR** - ETCS Data Only Radio;
8. **ERTMS** - European Rail Traffic Management System;
9. **ESC** - (ETCS System Compatibility)
10. **ETCS** - European Train Control System;
11. **GSM-R** - GSM for Railways;
12. **HDLC** - High-Level Data Link Control;
13. **HO** - Handover;
14. **ISDN** - Integrated Services Digital Network;
15. **MA** - Movement Authority;
16. **MT** - Mobile Termination;
17. **NRD** - Network Registration Delay;
18. **OBU** - On-Board Unit
19. **PS mode** - Packet Switching mode;
20. **RBC** - Radio Block Centre;
21. **RSC** - Radio System Compatibility;
22. **TDMA** - Time Division Multiple Access;
23. **TSI** - Technical Specifications for the Interoperability of the railway system;
24. **UIC** - Union Internationale des Chemins de fer;
25. **QoS** - Quality of Service.

ZAKŁÓCENIA RUCHU POCIĄGÓW W SYSTEMIE STEROWANIA ERTMS

W artykule podjęto dyskusję prowadzącą do wskazania możliwych przyczyn zaburzeń w ruchu pociągów pod nadzorem europejskiego systemu sterowania ruchem kolejowym ERTMS. W następstwie wykrytych zdarzeń dochodzi do nieintencjonalnego wdrażania procedury hamowania pociągu pomimo braku obiektywnych przesłanek do takiego zachowania. Zasadniczo, w artykule przedstawiono system ERTMS jako system czasu rzeczywistego oparty na dwóch podsystemach ETCS i GSM-R. Każdy z tych podsystemów posiada część pojazdową i infrastrukturalną. Na wstępie artykułu wskazano na ogólne przesłanki mogące mieć wpływ na brak zachowania kompatybilności pojazdu i infrastruktury torowej wynikającą ze zmian w kolejnych wersjach specyfikacji (baseline). W dalszej części artykułu przeprowadzono proces prowadzący do hamowania pociągu. W dalszej części artykułu odwołano się do scenariuszy ETCS i parametrów mających wpływ na reakcje systemu w czasie działania. Odniesiono się do uwarunkowań transmisji wiadomości pomiędzy naziemną infrastrukturą ETCS i pojazdem poprzez sieć telekomunikacyjną, w tym GSM-R. W końcowej części skupiono się na przyczynach i następstwie wdrażania hamowania pociągu będących konsekwencją nakładania się granic obszarów sterowania ruchem kolejowym objętych obszarami odpowiedzialności RBC i obszarami komórek sieci radiowej GSM-R. Artykuł kończy krótkie podsumowanie i wnioski.

Słowa kluczowe: zaburzenia ruchu pojazdów, ERTMS, systemy czasu rzeczywistego, QoS

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