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CRITICAL ASSESSMENT OF ERTMS SYSTEMS RELIABILITY BASED ON THE EXAMPLE OF THE GSM-R SYSTEM

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Abstract

It can be assumed that at least some of the systems associated with the train traffic operation work in the "mission" mode, i.e. their availability and operational dependability are related to safe "move" of a train through the strictly defined section of the railway line, i.e. systems (devices) must operate reliably during "mission". In the remaining time, operation of devices does not affect the safe train traffic operation. For example, it is possible to list crossing signalling systems or the GSM-R system, which along with the ETCS 2/3 system, constitutes the ERTMS system.

In the article, the GSM-R system operation analysis, in terms of the above-mentioned factors, is presented. In general, it can be assumed that the GSM-R system devices (e.g. BTS base stations) should be efficient within the specific periods, i.e. during the train passing through the relevant section of the railway line. According to the authors' calculations, it is stated that within longer periods, the selected GSM-R system devices (BTS stations) cannot be fully efficient, i.e. possible failures occurred and removed in these periods will not affect the safe train running.

Keywords: *exploitation, reliability, availability, ERTMS, GSM-R*

1. Introduction

In case of train traffic, control systems constructed on the basis of the microprocessor technologies, in which appropriate software must be installed for obvious reasons, other device assessment methods than the already used ones should be applied in terms of their reliability, availability and operational dependability. Reliability, availability and operational dependability constitute the factors that directly affect the safe train running.

A characteristic feature of programmable computing devices is the fact that possible failures of these devices do not always have an impact on these devices' basic function fulfilment, e.g. application of appropriate redundancy in the devices and properly chosen switching times to correctly operating redundant elements can result in the situation that the device, from the user's point of view, will perform its function in an uninterruptible manner. Another example is the fact that the devices should be available and dependably perform their functions in a specified period of time and in a specific traffic situation, e.g. during the train passing through the relevant section of the railway line, and the devices should be in a state of readiness in the remaining time, and then a possible failure may be "invisible" while fulfilling basic functions of a given device.

GSMR networks are used worldwide, also in European countries. In the nearest future GSM-R is going to be built also in Poland. Communication system currently used by Polish railways, occupying 150 MHz has already been exploited, and therefore does not meet current technical requirements, norms and standards and does not obtain required functionality. Assumptions of International Union of Railways (UIC – French: Union Internationale des Chemins de fer) took into account mainly unification of European railway communication systems by implementing EIRENE (*European Integrated Railway radio Enhanced Network*) project [9]. Implementation of

GSM-R has measurable financial benefits for railway sector. The capacity of railway lines highly improves and state border crossing time is reduced to minimum. Thereby the provided services level increases (e.g. by implementing parcels monitoring). GSM-R is a digital mobile network used for needs of railway transport. It provides digital voice communication and digital data transfer. GSM-R offers developed functionality of GSM. Its infrastructure is located nearby railway line. GSM-R is designed to support systems implemented in Europe: ERMTS (European Rail Traffic Management System) and ETCS (European Train Control System), which task is to collect and transfer continuously rail vehicle data, such as speed or geographical location. GSM-R is a transmission medium for ETCS, it mediates information transfer to a driver and other rail services. Implementation of mentioned above systems indeed improves railway traffic safety, allows to diagnose railway vehicle in real time and to introduce parcels and cars monitoring. Moreover, due to precise distance definition between two trains the capacity of individual railway lines can be highly increased.

2. Existing state issues

While implementing the EIRENE (*European Integrated Railway radio Enhanced Network*) project, the International Union of Railways (UIC) mainly took into account unification of the European railway communication systems. The GSM-R system implementation has considerable financial benefits for the railway segment. The railway line capacity is significantly improving and the level of provided services is increasing. GSM-R is a digital mobile telephony system used for the railway transport, which provides digital voice communication and data transmission. GSM-R is characterised by infrastructure located only near the railway lines.

he GSM-R system with the ETCS *(European Train Control System)* system constitute the ERTMS (*European Rail Traffic Management System)* system, i.e. the European Rail Traffic Management System, which is aimed at continuous collection and transfer of data related to a rail vehicle, such as speed or geographic location. The GSM-R system is a transmission system for ETCS, mediates the transmission of information to the engine driver and other rail services. This action resulted in an increase of the GSM-R system role within the field of the safe train traffic operation.

The task of any telecommunication network is to transfer information within the specified time and with a specific bit error rate. The GSM-R network is a telecommunications system, which must be characterised by high reliability and provide the high safety level of transferred data in the railway environment. The determined GSM-R network availability is a very important issue for the Railway infrastructure manager, because it has a direct influence on the railway traffic safety and flow.

The GSM-R system basic service is to provide data transmission for the ETCS system, and the voice communications for the purposes of communication between a train crew and "a ground and mobile rail personnel" is an additional service. In the context of availability or reliability, the data transmission service is definitely more demanding than the voice transfer service.

The ERTMS system consists of two systems, i.e. ETCS and GSM-R. As far as the ETCS system has the numerically specified safety level SIL at the level of 4, i.e. $10^{-8} \leq THR \leq 10^{-9}$, the GSM-R system does not have any figures related to its safety. The lack of the data results in the situation that it is difficult to determine the ERTMS system safety level. It is crucial because within requirements, both system (SRS) and functional ones (FRS), there are no requirements concerning the GSM-R system availability, however, the ETCS availability values are presented. According to the UIC ERTMS Users Group's document called "ERTMS/ETCS RAMS Requirements Specification Chapter 2 – RAM", as of 30 September 1998, the ETCS system availability (hardware) was calculated, on the basis of certain assumptions, at the level of $A = 0.99985$. The Italian railway adopted the same availability factor for the GSM-R system (with teletransmission) while calculating the ERTMS system availability for the high-speed railway.

The GSM-R system is constructed based on the GSM public system, which provides it with continuous development in terms of technical solutions resulting from the technological progress of GSM implemented in public networks. At the same time, it should be stated that the GSM-R system is a tool for more efficient management, control and steering of the railway traffic, so that the GSM-R system is much greater "responsible" than GSM public systems, hence additional solutions to increase their safety must be implemented in these systems. Therefore, the issue to ensure the system operation continuity, correct radio coverage of railway areas and information security are becoming essential.

The increase in the information transmission dependability by the GSM-R system is obtained by providing adequate radio coverage, which is dependent on the train speed, along the railway line. Thus in case of the speed lower than 220km/h, the coverage level should not be lower than –95dBm, however, in case of the speed higher than 280 km/h, it should not be lower than –92dBm. The possibility of coverage with these levels should not be lower than 95% for each 100 m of the railway line; however, switching between two cells (*handover*) should be implemented along the railway line in normal conditions, not worse than 99.5%. Calls with the highest priority (alarm) should be executed in less than 2 s (for 95% of calls).

Within the GSM-R system, the quality of services QoS (*Quality of Service*), which includes a certain probability of a fake call, data transmission (transfer) delay, limited jitter (delay change within the assumed limits), the assumed BER *(Bit Error Rate)*, is an important parameter that demonstrates the system proper operation.

Telecommunication security is understood as a set of methods and mechanisms, the use of which provides the required level of radio coverage, availability and service continuity by selecting the appropriate system structure and network topology. The GSM-R system purpose as well as its impact on the railway traffic safety requires designers to ensure the system resistance to damage and interference.

It is extremely important to develop a strategy ensuring the maintenance of the necessary level of security as well as the preparation of plans for the system operation in situations of extreme danger. These scenarios are referred to as Disaster Recovery (infrastructure recovery after failure), and they constitute processes and procedures related to recovery and maintenance of technical and critical infrastructure for a given organisation after natural or man-made disasters.

3. Telecommunications security in GSM-R system

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The GSM-R system consists of two subsystems:

- GSM-R (track side),
- GSM-R (on board).

In the current deliberations on the ERTMS system, ETCS and GSM-R systems are considered independent, which is presented in many documents by the following formula:

$$ERTMS = ETCS + GSM\text{-}R. \tag{1}$$

As already mentioned, the ETCS system has a numerically determined safety level; however, the GSM-R system does not have any numerical parameters of safety, reliability or availability, which could clearly define the system in this respect. Numerical parameters could explicitly determine whether the measures taken to increase the GSM-R system reliability and availability are justified by operational and economic reasons [9].

The distribution of base stations in the GSM-R systems may take place in various ways depending on the required safety of provided telecommunications services (voice transfer and data transmission). The choice of the base stations' distribution and connection should be dictated by the railway line class and purpose, its capacity and the required level of safety. In the UIC documents, it is suggested that the GSM-R system architecture on the railway lines equipped with the ETCS system should be redundant. In case of the GSM-R system, the BSS subsystem redundancy should be completed with dual radio coverage implemented by the BTS base stations (co-located or alternating) and multiple BSC controllers distributed in various points of the railway network, which are connected to the NSS subsystem. The NSS subsystem should be duplicated and spatially distributed, i.e. the duplicated NSS subsystems' fundamental components, e.g. MSC, as well as HLR and VLR registers, etc., should not be installed in the same buildings (preferably in different places) [2].

In practice, such solutions are used by the majority of the Railway Infrastructure Managers. It is obvious that the greater redundancy is, the more reliable the system is, which means shorter time of the system unavailability during the year. However, along with an increase in hardware redundancy, the system investment and maintenance costs also increase and the delay effects resulting from switching between the GSM-R system redundant components must be also taken into account.

The GSM-R system data transmission supports four principal groups of services:

- sending text messages,
- main data transfer applications,
- automatic fax,
- train control supporting applications.

Text messages can be sent in two ways: point to point between two users or broadcast to many users at the same time.

The data transmission service is connected with the remote control over on-board and traction devices, automatic train traffic control, control of the rail vehicle traffic safety, and applications designed for passengers. Among the applications for the rail transport passengers, it is possible to find information about train schedules, weather, and access to the Internet.

In the GSM-R network, GPRS (*General Packet Radio Service*) packet transmission methods and EDGE *(Exchanged Data rates for GSM Evolution),* known for public solutions, are implemented. The GPRS packet transmission – is to be used mainly by transmission of signals between the track and vehicle (in case of the ETCS system installation).

Railway emergency calls REC (*Railway Emergency Call*) are designed for drivers, train dispatchers and other specified railway workers. The task of the REC transmitted calls is to inform the particular personnel about possible obstacles affecting the railway traffic operation safety, which can relate to stoppage of this traffic within the assumed area or taking other actions to provide the safe train traffic operation (e.g. train speed limit at a specific section of the railway line). The REC emergency call must be transferred to all the concerned within the defined operational area.

The safety increase of information transmitted in the GSM-R system was achieved, among others, by the use of a different frequency than in the GSM public system. The GSM-R system operates in the 876-880 MHz band (uplink – communication towards network) and 921-925 MHZ (down link – communication towards terminals), which effectively separates this band from the GSM system band (operating, respectively, in the 890-915 MHz and 935-960 MHz bands). The increase in reliable information transmission by the GSM-R system is obtained by providing adequate radio coverage, which is dependent on the train speed, along the railway line, therefore:

- the data transmission purposes: for speed lower than 220 km/h, the coverage level should not be lower than –95 dBm and for speed higher than 280 km/h, the coverage level should not be lower than –95 dBm.
- for the voice transmission purposes, the coverage level should not be lower than –98 dBm.

The possibility of radio coverage of a specific level should not be lower than 95% for each 100 m of the railway line; however, switching between two cells (handover) should be implemented along the railway line in normal conditions not worse than 99.5%.

Within the GSM-R system, the quality of services *(Quality of Service – QoS)*, which includes a certain probability of a fake call, data transmission delay, data transmission delay, periodical deviation within the assumed limits (the so-called jitter), the assumed bit error rate, etc., is an important parameter that demonstrates the system proper operation.

Telecommunication security is understood as a set of methods and mechanisms, the use of which provides a high level of the system availability and reliability by selecting the appropriate system structure, among others, redundancy of individual elements. The GSM-R system purpose as well as its impact on the railway traffic safety requires designers to ensure the system resistance to damage and interference.

The GSM-R system architecture should be designed in a way, which allows for minimum interruption in providing services in case of damage to one or more elements. It is achieved with the use of a combination of hardware redundancy and network resistance to damage of individual network elements. The consequence of a serious failure of the GSM-R network is interruption in the service provision in the entire rail network or its part in a longer period than it results from the defined maximum repair time [1, 8].

The *Disaster Recovery* planning is part of a larger process of the operation continuity planning and it should include a definition of the procedures for recovery of application, data, hardware and communications. During the network design process, some scenarios, in which the system's individual elements tend to fail or damage, e.g. due to fire or disaster, are assumed. By predicting this type of events, it is possible to specify critical elements for the entire system functioning and select the appropriate method of their protection. Redundancy is a natural method that allows to increase the network reliability, safety and availability, and it means redundancy of assemblies, subassemblies or elements. It refers both to information stored in the registers and to the hardware elements, which can be duplicated in different ways, inter alia, n+1, 1+1, 1:n. The operation of these systems can be performed in various ways, e.g. under hot or cold reserve. Redundancy may refer to making copies of all data or only the data, the value of which is particularly important. In case of redundancy of the system components, the following elements may be subject to redundancy:

- the entire system,
- individual subsystems, e.g. BBS base stations, commutation and network NSS, OMC operation and maintenance centre,
- individual elements included in the subsystem, e.g. MSC centre and HLR register,
- individual components included in the subsystem elements, e.g. MSC processor cards, interfaces.

Apart from duplication of individual system elements, redundancy is also used for the components such as MSC processor cards or interfaces. This type of redundancy is called "internal redundancy" and is currently used by all manufacturers of the GSM-R hardware.

It is not possible to agree to all of the above-presented arguments. The claim that it is sufficient for the GSM-R system to meet only the requirements which are fulfilled by the GSM public system is large underestimation of the GSM-R system role in the ERTMS system, because:

- the GSM-R system transmits data directly associated with the ETCS system, i.e. related to the railway traffic safety,
- the system must generate and receive the REC signal, which is also related to the railway traffic safety.

– in the documents signed by UIC, there is a clear suggestion, confirmed by practice, that the GSM-R system architecture should be redundant (dual radio coverage, dual NSS). However, there are no such suggestions in any recommendations for the GSM public networks and it is hard to find the GSM public operator, which would have 100% redundant infrastructure.

According to the authors, the UIC recommendations in terms of data transmission safety through the GSM-R system are not harmonised with each other, because if the GSM-R system has to be the same as the GSM system [7] – then what was the reason for introducing an obligation to maintain the above-mentioned radio coverage level, dependent on the train speed limit for a given railway line?, This coverage should be maintained at 95% of the length of each 100 meter railway line section. Why the radio coverage measurements are to be carried out with accuracy of 0.1 m? The time period of a radiomodem in case of the "radio hole" with a length of 5 m and the train speed of 200 km/h is 90 ms, and in the "hole" with a length of 0.1m – 1.8 ms, while it is specified that the information transfer time from the trackside automatic devices to the driver desk is on average slightly more than 4 s. In case of the system requirements (SRS), a concept of a time interval between applications (T_NVCONTACT), the exceeding of which results in the system response by the M_NVCONTACT action, e.g. starting the train braking process, was introduced. T_NVCONTACT time was determined by the individual Railway Boards and ranges from 6 s (Spain) to 60 s (Netherlands) [3].

4. Author's analysis of the discussed issues

ERTMS/ETCS system of level 2 consists of three systems:
– onboard system,
– trackide system,
– GSM_R system.

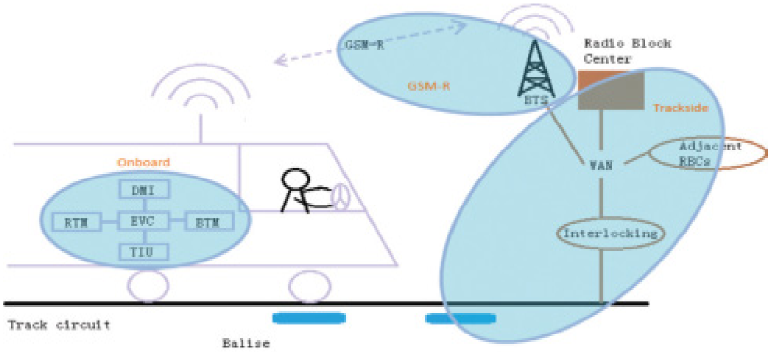
The on-board system is installed in a train and it is used for the train control based on received information from the trackside system, and it creates a "braking curve". According to this curve, the train speed, which depends on the speed limit of a given section of the railway line, the distance from the "stop" signal or a dangerous place, is profiled. The on-board system also receives information from balises placed in the track and sends a report about its position to the trackside system via GSM-R system. If a driver does not operate the train in accordance with the procedure that is in force in that time (e.g. it does not include the speed limit), the on-board system automatically activates the braking procedures, which start the appropriate train devices.

The trackside system controls the train drive, determines the location and transfers data on the speed correction of a given train. The trackside system contacts with the train traffic control systems through a separate RBC *(Radio Block Centres)* system and Eurobalises.

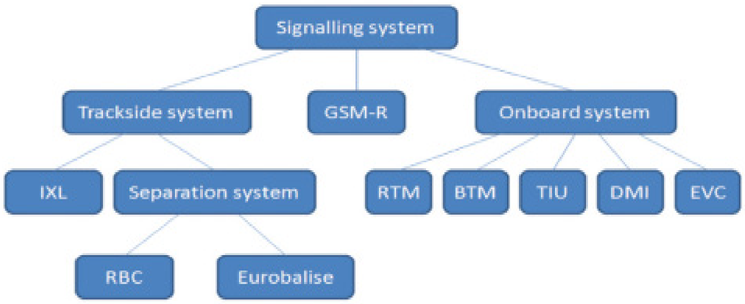
The GSM-R system is an international standard for the railway radio communications and railway applications. The communication direction is dependent on the frequency band:
– "train – track" direction 876-880 MHz band,
– "track – train" direction 921-925 MHz band.

All three ERTMS systems, i.e. board system, trackside system and GSM-R system operate in parallel. All three systems begin their activities in the "Waiting" state (readiness to receive the reports), and after the "Start" signal, they change into different states depending on the transmission direction, data accuracy, transmission completion, etc. until they receive the "End" signal, after which they return again into the "Waiting" state. The next report may be sent in a specific time that is appropriate for a given railway line or in a completely random time, e.g. REC signal. However, mean time between failures (MBTF) consists of working time and readiness time.

Having regard to this state of affairs, the ERTMS system model should be described as follows:



(a) Architecture



(b) Hierarchical structure

Fig. 1. Architecture and structure of the ERTMS system (source: [6])

$$\text{ERTMS} = \text{ETCS} \cap \text{GSM-R}. \tag{2}$$

The further analysis will be carried out for the maximum requirements for the GSM-R system, i.e. in case of the data transmission service for the purposes of ensuring the safe train running by the ETCS system level 2/3. Other services provided by the GSM-R system, e.g. the *Voice* service, have lower requirements in the field of the system reliability and availability.

The GSMR system is a hardware and software system *(Network-Centric Systems)*, and basically a traditional formula for the GSMR system availability:

$$A = \frac{\text{MBTF}}{\text{MBTF} + \text{MTTR}}, \tag{3}$$

it hides the system reliability. Highly available systems can be very unreliable.

In the hardware and software systems, a large part of failures includes software errors (failures), e.g. system suspension, software errors, which appear during the system operation, etc. These errors are detected and removed by the testing and diagnosing software, very often in short periods of time (milliseconds, seconds). The second factor affecting the hardware high availability at relatively low reliability hardware and software redundancy, used in the systems, which also make it possible rapidly remove the failures (switching from the damaged unit to the reserve one). The switch can also last for a relatively short time.

According to some publications (4), a concept of “reliability” for the hardware and software systems should possibly be replaced with a concept of “dependability”, which defines the systems’ states better.

The GSM-R system trackside part consists of several subsystems, e.g. BSS, NSS OMC, etc., the failures of which may affect the railway traffic operation safety or they do not have such an impact.

According to the authors, the incidents (alarms) occurring in the GSM-R systems can be divided into:
– critical, e.g. data transmission interruption,
– important, e.g. a loss of redundancy but without a loss of data transmission,
– of minor importance, e.g. opening the door in the BSS station – without a loss of data transmission.

In addition, the incidents, depending on the place they occurred, may affect only its operation area, and thus:
– the failure including the data transmission break in the NSS subsystem operates within the entire area of the NSS system operation (practically on all the railway lines supported by NSS),
– the failure in the BSC station causes a negative effect only on the railway lines, which are supported by this station,
– the failure in the BTS station causes a negative effect only in its operation area (it can be e.g. about 7 km of the railway line), and only if:
  – the train occurs in the failure duration within the cell operation area (EDOR terminal),
  – the RBC message will be sent at the same time,
  – the transmission interruption time will be longer than T_NVCONTACT.

The GSM-R system operation dependability primarily depends on critical failures, i.e. sufficiently long data transmission interruption, that is the interruption, which may result in the implementation of emergency braking procedures[1]. In case of the BTS base stations, the failure occurrence time is also important. The possibility of critical failure harmfulness in the BTS base station operation area is a time function of the train staying in a given area, failure duration time, frequency and length of the sent telegrams, as well as the time interval between successive trains, which can be described by the following formula:

$$P_{ki} = f(v, l, t_o, t_h, \omega, w)\,, \tag{4}$$

where:
P_{ki} – the failure harmfulness possibility in the BTS base station operation area,
v – train speed,
l – the cell operation area length,
t_o – the failure duration > T_NVCONTACT,
t_h – time interval between trains,
ω – frequency of sent telegrams between $ETCS_{trackside}$ and $ETCS_{onboard}$,
w – size of telegrams in bits.

According to the SRS ETCS orders, the frequency of sending telegrams by the ETCS system is included within 1 – 254 s, and the reports' size is 250 bits. For the purposes of this paper, the authors coined the term "mission" that means the train radio control by a specific BTS base station. Missions are repeatable and the mission duration depends on the train speed and the railway line length supported by this station.

Mission time of a single BTS station – (t_p) can be expressed by the following formula:

$$t_p = l / v\,. \tag{5}$$

The duration of all the missions in the BTS station time unit can be expressed by the following formula:

$$T_p = \sum_1^n \frac{l}{v}\,, \tag{6}$$

[1] harmfulness of the failure also depends on the length of the free distance and the train braking distance as well as the time of receipt of a last signal from the control centre

where:
t_p – time of the train staying in the operation area of a given BTS station,
n – number of trains radio controlled by BTS in the time unit[2],
l – railway line length supported by the selected BTS station,
v – train speed in a given cell,
T_p – total staying time of n trains in a cell.

By assuming that the BTS station supports the railway line area with a length of 7 km and the train speed is v = 250 km/h, the train staying in the BTS station operation area is more than 100 s. By assuming the number of 30 trains per day, trains will stay in a single cell for a total of 6000 s, which constitutes 7% of a day, and it means that during 93% of time, even critical failures in base stations will not affect the safe train running.

At the same time, it means that MTBF consists of two components, i.e. the system operation time and system readiness time, and therefore the BTS base station availability can be expressed by the following formula:

$$A = \frac{\text{Operating Time} + \text{Operable Time}}{\text{Operating Time} + \text{Operable Time} + \text{Downtime}}. \tag{7}$$

If the failure occurs during the report transmission or reception from the vehicle control centre (or the other way around) and it lasts for an appropriate period of time, which will force interruption in transmission between trackside RBC – on board RBC, which, in turn, will cause interruption of exchanging telegrams between the ETCS applications and it will result in the implementation of the vehicle braking procedures, then the discussed failure will produce a negative effect. The recovery of the GSMR system signal transmission will firstly result in resynchronisation of devices at appropriate levels, and then transmission of data related to the safe railway traffic operation and reaching the train speed limit on a given section. The result of such a failure will include loss of energy, train delay[3], the determined possibility of causing slowdowns of trains following this train and of trains on the tangent lines to the considered railway line.

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3. Conclusion

The same analysis should be carried out for the BSC station. In practice, BSC stations have large hardware and software redundancies, and their reliability is at a level of at least 99.999% (BSC station unavailability amounts, on average, to 3 min. per year).

A similar analysis should also be conducted for other GSM-R subsystems (i.e. NSS, OMC, HLR), taking into account their impact on the operation area size, time of critical failure removal,

[2] including the frequency of sent telegrams and potential mission duration – not every train in a given cell will be controlled by radio.
[3] braking is more "aggressive", e.g. $0.5M/s2^2$ than acceleration of only $0.3 m/s^2$.
[4] braking is more "aggressive", e.g. $0.5M/s2^2$ than acceleration of only $0.3 m/s^2$.

harmfulness of failures and the impact of random events (fire, lightning, flood, etc.) on the entire GSM-R system operation dependability.

The critical service for the GSM-R system includes a data transmission service for the purposes of the ETCS system. The GSMR system reliability and availability, as the most important parameters for the safe train running, should have specified figures. While determining these figures, the dynamics of changes on the railway line during the travel of trains should be taken into account. The various subsystems of the GSM-R system (BSS, NSS) should be individually assessed in terms of reliability, including the dynamics of the processes.

The risk of harmful effects related to the previously defined critical failures of the GSM-R system, which may affect the uninterrupted train travel, should be assessed.

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