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A Novel Method to Improve the Defense Security of Railway Transportation

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ABSTRACT

Rail transport is used not only by the civil sector but also by military transportation. This duality makes it crucial to maintain the functionality and security of the system. This research aims to determine the combined impact on maintaining the sector's functionality by analyzing the elements of civil transport safety and military defense security. The result of the research is the definition of a new evaluation index (RDSI) as a synthesis of the security and security factors, which can consider transport safety and defense security requirements. The calculated value of the index provides an idea of the civil safety and military security improvements needed on a railway line, thus increasing the level of protection and resilience of a country. Further use of the index can help to identify weak points of the rail transport system, give an idea of the protective utility of a railway line, find bypasses, and improve the impact of climate change on rail transport. The effectiveness of the index is demonstrated through a case analysis.

1. INTRODUCTION

The aim of transport is to enable the movement of people and goods required for almost all aspects of social and economic life to be carried out as quickly and safely as possible. In the military field, transport is also essential as a vital means of carrying goods and staff for operations and defense. Since human life is of high importance in society, efforts must be made to reduce the risk of displacement, i.e., to achieve an adequate level of safety in transport. Transport safety is a state in which transport users can execute a change of position free from hazards, accidents, and disturbances. The level of transport safety in a given geographical area can be considered as a joint (social) production of the people living and driving there.

The security of transport systems is, therefore, primarily about protecting the functioning of the system, but the high financial and social value of infrastructure means that the individual elements themselves also need to be protected. Owing to this high value, transport systems are considered critical infrastructures, and their protection is a matter of national security and, therefore, a task for the (military) defense sector, which must prepare the elements of the system for any problems or emergencies that may arise.

However, the tasks of this protection training also impact transport safety by virtue of the protection itself. Some security measures can increase transport security by, for example, requiring the use of technical solutions to increase resistance. The question arises as to where protection safety can be realized in measures to increase transport security and how their impact can be measured.

The relationship between transport safety and security is an interesting issue because both values are important in society. It is needed to examine how safety measures that protect everyday life affect a country's military defense capabilities. This is particularly true for the rail system, which is at the forefront of transport safety. The railways can be of great assistance to land movements during military transport, and it is therefore of vital interest to ensure the operation of the system.

Research on safety and security has examined both elements, but it has mainly focused on transport safety, with little research on the relationship between the two.

Based on the above, the study seeks to answer the following research questions:

- Is there an explicit relationship between traffic safety and defense security?
- How can this help to increase a country's security of defense and resilience?
- What further implications can this link have for rail transport?

These questions can be answered by using a novel method, including a security index based on theoretical research, which can determine a railway line's protection capability and the development needed to achieve it.

In the first part of the study, the interaction between transport safety and defense security is examined. After analyzing the railways' transport safety, the defense security of the subsector (the tasks of military preparedness for protection) and the railway defense security index (RDSI) will be defined. The index illustrates the impact of safety measures on rail transport security and vice versa. In the second part of the article, the practical application of RDSI in military security and railway operations is presented.

The index's application provides a new approach to preparing the rail transport system for safety and raising the level of safety by addressing these safety requirements together. Further use of the index can also ensure the sustainability of rail transport in a wider context.

2. LITERATURE REVIEW

Due to the size and importance of the subject, the protection of critical systems is addressed by academic research institutions and governmental organizations, so the available literature is very extensive. The research and literature deal with the planning of critical infrastructure, focusing mainly on the protection of critical elements and the systems that contain them, on enhancing their robustness, and examining the internal relationship of such aspects [1]. So far, only a few research deals with the impact of enhancing the level of protection on functionality. This includes a Czech study in which the authors present an indicator of resilience that takes into account the limit of acceptability of the loss of functionality associated with an increase in resilience [2]. The application of the mathematical model developed is demonstrated on critical elements in a selected area of the Czech Republic. Another study uses the importance index to determine the weight of certain critical infrastructure elements and, thus, the need for protection [3].

Further scientific research looks at the protection options for the transport system as part of critical infrastructure. These include, for example, a model for the deployment of railway rescue units combined with a fuzzy logic approach [4] or a model for the robustness and resilience of the network, taking into account the specificities of passenger transport [5]. The American authors of one book give a good overview of the subject but define the complexity of rail infrastructure protection only in terms of cooperation [6]. Most research and studies, including those by Delft University, have a similar orientation in terms of the resilience of transport networks but do not address the impact of resilience on transport safety.

In aviation, it has already been recognized that civil-military interoperability in the field of infrastructure will allow the necessary capacity increases and security improvements for the development of civil aviation [7], and the technology for primary screening has also been developed [8].

In the context of motorway developments, researchers have highlighted that the multi-level servicing of critical access links considered in the design process greatly increases the robustness of the road transport system [9]. Indonesian researchers have found that the use of critical transport infrastructure with computer-aided design can encourage robustness in the face of natural phenomena (tsunamis) [10]. This requires knowledge of the load-bearing capacity of the infrastructure.

Enhancing the system's robustness by increasing the waterways' throughput capacity, i.e., expanding the use of locks as water transport infrastructure, can contribute to the stability of inland navigation [11].

The results of research into the transport safety of the rail sector can be applied to construction work [12], operational traffic and safety management [13-18], interlocking systems [19], infrastructure inspection [20], and robustness value [21].

The focus of defense safety research is mainly on the identification and assessment of security risks and the exposure of the sub-sector to terrorist threats. Research into the security of rail transport as critical infrastructure is being carried out by several organizations. One such organization is UIC, where the Sherpa program provides the framework for defense research [22]. The European Union has set out its European Programme for Critical Infrastructure Protection [23] in its Green Paper. NATO's critical infrastructure protection efforts originally focused on how to help member states improve their preparedness against terrorist attacks on critical infrastructure in order to protect civilians [24]. The latest thinking of the organization is that critical infrastructure protection aims to address the effects of natural, accidental or deliberate civil disasters that threaten the security of life and property [25].

The American view is that critical infrastructure facilities and their services are the pledge of national defense, a strong economy, and the health and safety of citizens [26], while Northern European countries have adopted the view that infrastructure is necessary for the functioning of vital societal functions [27], i.e., protection against all hazards is necessary, which is primarily ensured by increased resilience. In terms of resilience, Grass argues that it is necessary that the essential functions of the (transport) system are maintained in the face of an extreme event [28], while system vulnerability means that a structure (e.g., a component of the railway infrastructure) is not able to withstand the forces of a given hazard [29]. A study on the economics of rail safety concludes that it is necessary to include the costs of protection in the (investment) costs of the system [30], i.e., a criterion is needed that indicates the need for protection investments for a given development. Meanwhile, researchers have also formulated the conditions for the protection of certain infrastructure elements [31-33].

Another important area of rail transport security is cyber security. In this area, research has been carried out into improving the level of protection available for rail-road crossings [34], the use of drones [35], and blockchain technology [36, 37].

In the rail subsector, research results also state that rail infrastructure must meet both civil and military transport and technical needs [38] and that one way of achieving military mobility is to explore the potential of a civil-military approach to infrastructure development [39]. This is primarily the task of NATO's Host Nation Support, but there are no scientific publications on how to achieve this.

Researchers have identified the need to conduct research on the security risk management of military rail transportation and to develop countermeasures to address the problems and strengthen operations [40].

In a previous issue of this journal, Italian researchers defined vulnerability assessments for some strategic buildings [41]. This article presents a similar methodology for railway transportation.

From the literature review, it can be concluded that the methods of preparing railway infrastructure for defense in the context of transport safety and security can be seen as an unexplored area of research. This paper presents one of the results achieved in this research area.

3. SAFETY AND SECURITY APPROACHES OF RAILWAY TRANSPORTATION

3.1 Transport safety of railways

Technological progress has a major impact on rail safety, with increasingly advanced safety equipment providing greater security. However, new, immature technologies can also create dangerous situations. These emergencies can occur on the railway track, during the operation of safety equipment, and during traffic management.

One of the parameters of railway safety is technical safety, which means the technological perfection of the controlling and monitoring systems for train movement. It is measured by the difference between the safety dimensioning of the equipment and the danger limit.

In order to ensure accident-free rail traffic, in addition to adequate technical safety, it is necessary that the protection equipment does not fail during operation, i.e., that it is fail-safe. Even this cannot be fully guaranteed, so the next parameter of railway safety, operational safety, can be defined based on technical safety because operational safety is an indicator of the effectiveness in terms of the frequency with which individual pieces of equipment fail or are used up. Its extent is determined by the susceptibility of each piece of equipment to faults and the magnitude of the faults that can occur during operation (e.g., whether the equipment allows situations that could cause an accident).

The safety of rail transport can be guaranteed primarily by the proper functioning of various types of safety devices. Their basic task is to prevent accidents and hazards and to control train traffic. In all cases, ensuring that they operate correctly is a priority and an inseparable part of the task since accidents can only be avoided if traffic is properly controlled. This does not mean, of course, that the equipment is fault-free because the technical solutions are not perfect, and it is, therefore, necessary to supplement operational safety with a third parameter of rail safety, namely traffic safety. Traffic safety is an indicator of the effectiveness of operational safety, i.e., the frequency of accidents resulting from equipment failure. The aim of traffic safety is to have (traffic) rules for failures of safety equipment. Traffic safety can, therefore, be achieved through knowledge of and compliance with instructions, regulations, and rules and through the controlled cooperation of all actors in rail traffic.

The control of train movements, i.e., the management of maneuvering on the tracks (train movement and shunting), which is necessary to avoid accidents, to ensure that traffic operations can be carried out, and to ensure scheduling, is mainly achieved by the management of safety devices and the system of instructions. Traffic flows are realized by operating the external and internal objects of the safety equipment and the on-board equipment (e.g., switch, signaling, train controller, etc.). The control of traffic is facilitated by various auxiliary devices, which mainly perform control functions.

As most railway traffic activities are performed or supervised by humans, the effectiveness of the parameters defined above depends primarily on the human factor, i.e., the level of awareness among the operating staff of the technical and operational safety of the equipment and their expertise in traffic safety. This is compounded by work errors due to skills and motivational problems. It follows that the safety of rail traffic is primarily a human factor and that most of the hazards or incidents that occur are due to human error.

Such extraordinary events are usually the result of several simultaneous deficiencies or omissions or unavoidable external causes. Incidents always cause disruption to rail transport. The extent of the disruption depends on whether the consequence of the event is a complete closure of the railway line or the possibility of maintaining train traffic.

3.2 Defense security of railways

Rail safety must be considered not only from a transport perspective but also from a defense perspective. The creation of defense security further enhances transport safety, as it has a positive impact on technical safety and increases operational safety. As mentioned above, operational safety measures the susceptibility of devices and equipment to disturbances and faults, and defense security can reduce these. Defense security can be achieved primarily by protecting critical infrastructure elements.

A national railway infrastructure has many elements that not only serve a country's mobility needs but also cover the movement of traffic within a continent and even between continents. It is quite natural that not all elements of the network can or should be considered protected.

Since the spread of terrorism, the way in which potential risks of critical infrastructures are calculated and analyzed has expanded. The definition of risk should take into account the threat, the components of vulnerability of the system or element, and the expected consequences of the eventual occurrence of an incident. Therefore, it is necessary to identify which elements of the railway infrastructure are considered critical system elements that need addressing in the context of preparedness.

It is also important to see that the operation of each infrastructure can be interdependent, i.e., the state of one infrastructure affects the state of the other or is related to the state of the other [42]. This is particularly true for the rail transport sector, which transmits resource demands between different sectors (e.g., the running of coal freight trains, which are transported by electric locomotives to supply coal-fired power plants that, in turn, generate traction energy for railways). This interdependence, as well as the possibility of multiplier effects of natural or man-made accidents, further increases the need to protect critical transport infrastructure elements.

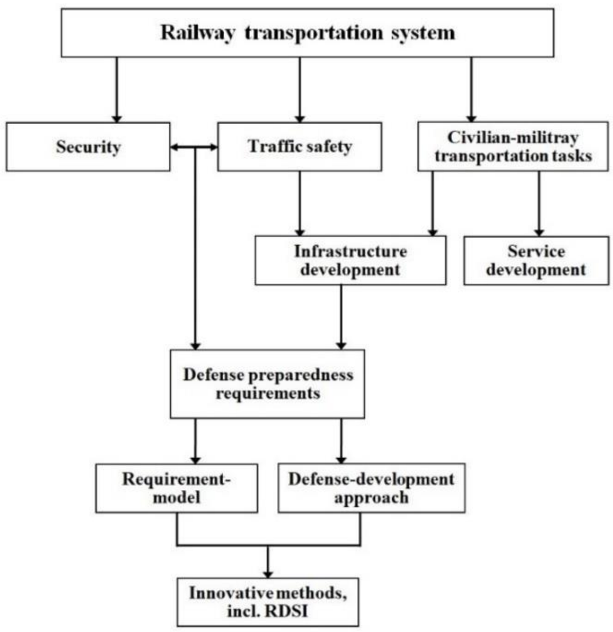

Figure 1. Relationship between rail safety and defense security through infrastructure developments

Therefore, it can be concluded that the level of safety in the rail transport subsector is a major determinant of preparedness for protection tasks in terms of its ability to help maintain operational capability.

The relationship between rail safety and defense security through infrastructure developments is shown in Figure 1. The figure shows that both transport and security needs determine the infrastructure development needs (in addition to service development needs), which must take into account the security requirements set by defense security and transport safety together. Together, the resulting requirements model and the security approach can deliver innovative solutions, such as RDSI, that serve transport development and preparedness for protection as well.

4. METHODOLOGY

4.1 The impact of defense and transport safety on each other: Defining the railway defense security index

The level of transport safety can be defined as an indicator by comparing performance against a set of requirements. In this way, in the case of rail transport, the performance of the infrastructure, i.e., the technical quality of the track, can be compared with the safety requirements using the following formula:

$$transport\ safety = \frac{technical\ level\ of\ the\ tracks}{safety\ requirements\ of\ the\ tracks}$$

The technical level is determined by the number of trains (N_s) that can run on a line, i.e., the throughput capacity of the line. According to 3.1, the safety requirements can be of three types: technical (SR_{te}), operational (SR_o) and traffic (SR_{tr}). To achieve transport safety, all three requirements must be met simultaneously. According to 3.2, safety requirements can be interpreted not only from a transport perspective but also from a security perspective. Critical infrastructure protection aims to improve operational safety by reducing the vulnerability of infrastructure elements to disruption. Therefore, the safety requirements for railway infrastructure are extended by the safety requirements for protection (SR_d). It follows that transport safety is also affected by the defense security requirements to the extent that the technical level of the track must also meet these requirements. Preparing for protection aims to meet the track protection defense security requirements. An important factor in the definition of protection tasks is which lines can be used for running additional emergency trains (N_e) and which lines need to be upgraded from a protection point of view. This is a key factor in establishing the appropriate level of resilience.

According to the above formula, the level of transport safety is therefore also influenced by the requirements of preparedness for protection. This statement is also true in reverse; i.e., the level of defense security of a railway line is affected by changes in the level of transport security.

The Railway Defense Security Index (RDSI) can be used to determine the safety reserves of a railway line (station spacing), i.e., to illustrate the relationship between transport safety and defense security. The index can be defined as follows:

$$RDSI=\frac{N_s+N_e}{SR_{te}+SR_o+SR_{tr}+SR_d} \quad (1)$$

To make sense of the index, it is necessary to quantify the numerator and denominator. The number of scheduled trains can be determined based on the number of allocated train slots. To determine the number of trains running in an emergency situation, the peak demand that occurs in such a situation shall be taken into account. This will vary from situation to situation and will depend on the danger and the spatial and temporal extent of the circumstances. Resilience requires the organizations involved in the defense of the country to be able to respond to an emergency event in the shortest possible time. The degree of this reaction depends on the severity of the event. In order to carry out the necessary tasks during a period of special legal order, in many cases, the immediate and even exclusive use of the transport infrastructure is necessary; i.e., there is a significant demand for the use of the transport infrastructure. After the necessary measures have been taken and the crisis has ended, the demand will decrease significantly and return to the low demand of the normal period. The rise of the demand curve that can be written from this depends on the severity and duration of the emergency situation. However, only the probability of the occurrence of certain events (crises) is known (for example, the occurrence of an earthquake or flood or even the beginning of an armed conflict); the number of trains to be operated in such situations can only be estimated. Nevertheless, security and safety organizations must always be able to meet their demand, even with such a rise in the demand curves. A necessary and sufficient condition for this is that transport infrastructures, including railways, must be available for (immediate) transport operations.

The requirements for each parameter of transport safety are determined by the technical characteristics of the railway line, because, as defined in subsection 3.1, these safety parameters are interdependent on the technical infrastructure. In particular, the defense security requirements are complementary to the technical safety requirements, thereby increasing operational safety. The line on which security requirements are to be considered is determined by the civil and military role of the railway line. The technical infrastructure may justify designation as a critical infrastructure element and therefore defense security requirements are also affected.

The capacity of a railway line depends essentially on the railway technology used, which includes the technical parameters of the track, the level of development of the safety equipment and the method of traffic operation. Accordingly, the traffic defense requirements are reflected in the through-capacity calculated based on the railway operating and protection parameters. Together they determine the level of service that the railway can provide.

4.2 The possible values of RDSI

A railway line is able to perform its defense tasks if the capacity of the track is greater than the number of trains it is intended to run, so the value of RDSI must necessarily be less than 1. However, the value of the index is different for each emergency situation, as explained above, but the value can be calculated by simulating each emergency.

The value of RDSI shows the reserve capacity of a railway line to meet the transport needs arising from the occurrence of an event. The lower the value of the index, the more the line is involved in security transport tasks. However, in certain qualified cases, defense security requirements may generate transport demand that can only be met by limiting the number of regular trains with unchanged line capacity. As the timing of the occurrence of each emergency situation is unknown, it is necessary that the rail transport system has sufficient capacity reserves to cope with sudden surges in demand.

A task of protection preparedness is to determine, from time to time, the RDSI per line based on the capacity calculated from the actual track parameters and, where the index rises above 1, to take the initiative to increase the traffic and defense security requirements or, where this is not possible, to determine the individual detours in order to provide the necessary reserve capacity as defined in the previous paragraph.

Methods that can help to reduce the value of RDSI below 1, i.e., to increase the capacity (increase the value of the denominator), include the following (which safety requirement is reinforced is given in brackets):

- Increasing the track speed (SR_{te})
- Double tracking (SR_{te})
- Electrification, use of alternative fuels (SR_{te}, SR_{o}, SR_{tr}, SR_{d})
- Upgrading the station or inter-station safety devices (SR_{te}, SR_{o})
- Replacement of human control by mechanical systems (SR_{te}, SR_{o})
- Application of modern construction and engineering techniques (SR_{te}, SR_{o})
- Increasing the number of trains with telecommunication devices between two stations (SR_{tr})
- Use of physical protection solutions (e.g., armed guards) (SR_{d})
- Application of cyber protection solutions (SR_{d})
- Cooperation between civilian and defense-security sectors (SR_{d})

In the denominator of the index, the traffic and defense security levels are added together, i.e., traffic safety also contributes to the increase of defense security by reducing the value of RDSI. This implies that transport safety and defense security together and in a mutually reinforcing way can increase the safety of a railway line; namely, the tasks of preparedness for the protection of the railway infrastructure are, to a large extent, determined by the transport and defense security requirements and their mutually reinforcing effects, the condition of the track and its accessories and the infrastructure investments to raise it. The necessary defense security requirements can be determined based on the civil and military role of each railway line.

5. RESULTS AND DISCUSSION

The RDSI has clearly defined the link between transport safety and defense security. Therefore, in this chapter, the further research questions will be answered so it will be shown how the use of RDSI, as defined as a result of research, can help to increase a country’s defense security and resilience and maintain railway operations, i.e., what further implications this index has for rail transport.

5.1 Definition of alternative routes taking into account defense requirements

In the previous chapter, the tasks of preparedness for defense were listed as solving the issues of substitutability of railway lines. The issue of substitutability is mainly relevant in the case of damaged lines, where the damaged element may take longer to repair and requires replacement or diversion until the repair or installation of the prop is completed. This, in turn, in the vast majority of cases increases the journey time, i.e., trains do not run according to the pre-announced timetable. The resulting delays will, in any case, lead to a reduction in service quality. Substitution by other transport sub-sectors requires further investigation.

The redundancy analysis can provide the appropriate answers [43]. According to the weighted graph theory model that determines the redundancy, highlighted stations are the vertices of the graph, while the open line (station spacing) and the other stations are the edges of the graph. Two criteria are involved in the choice of substitute paths [44]:

- The impact of the detour on travel time
- The impact of the detour on the path length

These two parameters appear in the edge weights, but the method takes them as determined and does not take into account additional parameters or measures that could positively influence the value of a given parameter. The use of the method in preparedness for protection will give a more accurate result if such parameters can be taken into account. The RDSI can be used to represent protection interests, so its inclusion in the shortest path search will further increase the effectiveness of the redundancy analysis. The RDSI takes into account the capacity conditions of a given line (station spacing), as well as transport and defense security requirements. A possible way to do this is to multiply the travel time or path length values by RDSI when calculating the weight of each edge in the Dijkstra algorithm [45] for determining detours, as this ensures that worse indicators will reduce the weight of the edgeless; i.e., worsen the substitute value of a given line (station spacing), due to an RDSI value less than 1. (In extreme cases, the RDSI value greater than 1 will even increase the weight of the edge.) When calculating the shortest paths, it is desirable to minimize the edge weight, but on a line with a high value of RDSI, if the line is not adequately protected, the diversion may lead to the development of incidents.

Using RDSI, the graph weights are as follows:

$$w_t^* = w_t \cdot RDSI \tag{2}$$

and

$$w_\ell^* = w_\ell \cdot RDSI \tag{3}$$

If the calculations show that no suitable alternative route is available, it may be necessary to restrict non-military rail traffic and ultimately divert it to another sub-sector.

The method can be used to determine whether individual line sections containing critical system elements can be substituted, i.e., whether detours are available.

5.2 Determining the weak points of the railway infrastructure

A country's railway network is made up of many elements, and it is necessary to identify those that are most vulnerable to damage. Since, with few exceptions, the lines run on the surface, the whole infrastructure is affected by natural hazards. From this point of view, it is not possible to identify priority elements but to identify vulnerable sections as weak points based on the redundancy analysis, substitutability parameters, and the low value of the so-called concurrency index defined in the previous paragraph. Trouble with these sections is capable of causing significant disruption to the traffic flow on the network.

The authors of a Hungarian study determined the value of the concurrency index as follows [46]:

$$CI = \sqrt{S_t \cdot S_s} \tag{4}$$

From this, the score S_t is important for the definition of the weak points. The timetable score S_s follows from the passenger timetable of the railway line and it is not relevant for substitution; it can be taken as 1 ($S_s = 1$). It follows that the concurrency index (CI_s) calculated for substitution will not be the geometric mean of the travel time and schedule scores but only the travel time score itself:

$$CI_S = S_t \tag{5}$$

Based on the relationship between the substitute and the original travel times, the value of the utility function S_t can be calculated as defined by the authors using the following formula:

$$S_t = \begin{cases} 100 \cdot \left(q - \frac{j_s}{j_o}\right), if\ q > \frac{j_s}{j_o} \geq 1 \\ 100 + 40 \cdot \left(1 - \frac{j_s}{j_o}\right), if\ 1 > \frac{j_s}{j_o} \geq 0.5 \\ 0, if\ \frac{j_s}{j_o} > q \\ 120, \quad if\ \frac{j_s}{j_o} < 0.5 \end{cases} \tag{6}$$

The inclusion of RDSI in the formula can further identify where the weaknesses of the network are. The value of q can be interpreted as the reciprocal of RDSI, because there is an inverse proportionality between q and RDSI; i.e., the lower the RDSI, the higher the substitution threshold of a given railway line. This is due to the fact that the value of RDSI includes safety requirements as capacity values, in which the number of trains that can be dispatched depends on the occupation time of the station spacing, i.e., the travel time between two stations. Thus, the value of q can be derived from the RDSI; namely, the substitution threshold takes into account the capacity utilization potential of the line. On this basis, the parts of the equation containing the value of q can be written as follows:

$$S_t = \begin{cases} 100 \cdot \left(\frac{1}{RDSI_s} - \frac{j_s}{j_o}\right), if\ \frac{1}{RDSI_s} > \frac{j_s}{j_o} \geq 1 \\ 0, if\ \frac{j_s}{j_o} > \frac{1}{RDSI_s} \end{cases} \tag{7}$$

and from the definition of RDSI as follows:

$$S_t = 0, if\ RDSI_s \geq 1 \tag{8}$$

The equations above state that a railway line (station spacing) is considered a weak point in terms of passenger traffic if the CI calculated by the value of the S_t score based on RDSI is not higher than 25 for any of the substitute lines. The CI can be extended to freight if the journey times are interpreted in terms of freight wagon turnaround times. In addition, the function S_t, defined by expressing the substitution threshold q by $RDSI_s$ gives the partial utility of the substitution capability of a railway line on the network for preparedness for protection.

The calculation can be performed for all the lines that can be replaced based on the redundancy analysis. The alternate lines shall be charged with the traffic to be diverted in proportion to the calculated utility. In the case where the entire traffic cannot be loaded on the set of substitute lines, i.e., a particular critical element would remain a weak point, an infrastructure investment shall be made on one of the substitute lines. In times of emergency, there are very rapid options for increasing capacity, depending on current telecommunications capabilities, which need to be assessed and applied in a given situation.

5.3 Case analysis of the value of RDSI and its effectiveness on defense security decisions

RDSI is essentially a measure of the defense utility of a railway line. In the following, the calculation methodology and the evaluation of the results are presented through Hungarian examples.

The main rail transit direction in Hungary is east-west. This railway line has two critical points. One is the bridge over the Danube and the other is the bridge over the river Tisza. The second case will be examined. The bridge over the river Tisza is located in the Szolnok – Szajol section. Assuming that the bridge will be unusable for some reason, it will be necessary to divert rail freight traffic or even to carry out defense transports on the surrounding railway lines.

Therefore, if the Szolnok – Szajol section is unusable for rail freight traffic, it is advisable to examine the Tisza crossings south of Szolnok. One of these possible railway crossings is the Lakitelek – Tiszaug bridge. This bridge is located in a 28.7 km long station spacing. The line has single track and is not electrified, with a track speed of 50 km/h. For traffic safety reasons, only 1 train is allowed between the two stations at the same time. No specific defense security requirements are specified. Thus, the number of trains that can run in 24 hours is 16 trains, according to UIC Leaflet No. 406 [47], with 2 hours of mandatory maintenance per day. According to the timetable on the website of the Hungarian Railway Capacity Allocation Directorate [48], the line is operated with 5 trains per day, i.e., the RDSI for normal period is 5/16= 0.3125, which gives a sufficient defense security value for the line. If trains are to be diverted to the line due to the failure of the Tisza bridge at Szolnok, only 5 train-pairs (= 10 trains) can be dispatched without the index rising above 1.

- A significant increase in the technical level (that means a significant investment effort)
- Double-tracking
- Dividing the station-spacing into sections, thus increasing the number of trains that can run simultaneously between the stations, by means of manpower and communication (emergency solution)

Figure 2. Rail routes between Szajol and Cegléd

In Figure 2, the original Szajol – Szolnok – Cegléd (blue) and the detour Szajol – Tiszatenyő – Tiszafüred – Lakitelek – Kecskemét – Cegléd (red) route is marked. Based on the timetables of the Hungarian Railway Capacity Allocation Directorate [48], the calculated running time for the detour route is 150 minutes, while the original route is 40 minutes. The calculated value of the concurrency index $CI_s = S_t = -55$ is significantly below the value of 25, so by default, this option is not an alternative for the Szolnok – Szajol route, but it is the shortest detour. This should be taken into account in any case.

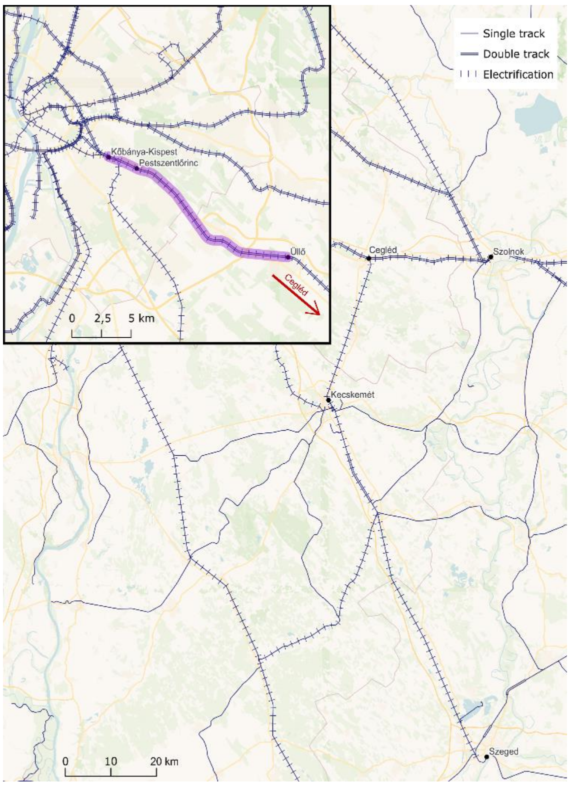

Figure 3. The examined railway section and cities

For the above reasons, it is not the RDSI value most relevant, but the number of additional trains that can be run at a given RDSI value. The Budapest-Kelenföld – Ferencváros section is the busiest station spacing in Hungary, as it contains Hungary's only double-track railway bridge over the Danube. All east-west rail traffic passes through here. The UIC capacity on the two tracks is 884 trains/day. In a normal period, 588 trains are running daily, so RDSI = 0.54. By RDSI = 0.81, 716 trains can run, i.e., 128 additional trains per day. This leads to the conclusion that the Danube Bridge has sufficient defense security capacity reserves and is, therefore, one of the most critical railway infrastructure elements in Hungary.

Figure 3 shows a double-track electrified railway line with a speed of 120 km/h near Budapest, Hungary. A theoretical timetable diagram of the purple section (Kőbánya-Kispest – Üllő) is presented in Figure 4 for a two-hour period. The black slots (train paths) are the regular trains, and the green ones are the extra trains that can be operated according to the rules (safety requirements). The diagram shows that 12 extra trains per hour are possible to run.

In Figure 3, three Hungarian cities were chosen along this railway line: Szolnok (population 67,000), Kecskemét (population 110,000), and Szeged (population 158,000) (source of the population data: Hungarian Central Statistical Office [49]). If the inhabitants of the cities should be evacuated by train in 24 hours because of an emergency, 67 trains would be needed to evacuate Szolnok, 110 to evacuate Kecskemét, and 158 to evacuate Szeged, using trains with a capacity of 1000 passengers. This number of trainsets is not available, so one trainset makes more turns, i.e., twice as many slots (engaged trains and empty trains) are needed, namely 134 for Szolnok, 220 for Kecskemét and 316 for Szeged. The figure shows that 24×12 = 288 extra trains can run on the line (RDSI = 1). This provides sufficient capacity for Szolnok and Kecskemét with RDSI = 0.808 and RDSI = 0.964, respectively. For Szeged, RDSI = 1.138, i.e., the line does not have sufficient defense security reserve in this case. It is, therefore, proven that the value of RDSI depends on the circumstances of the emergency and is different in each case, so it can only be calculated (estimated) for a specific (simulated) case and decisions according to the obtained value. The recently calculated values show that in the given example, the railway line has a very small defense security reserve for the rescue of settlements with a population of more than 100,000 inhabitants and that it may be worth considering capacity expansion, which means upgrading security requirements. One quick way to do this could be to temporarily reduce the slot time, i.e., to slightly ease traffic safety requirements. In Figure 5, the slot time (SRtr) has been reduced from 5 minutes to 3 minutes, resulting in 8 more trains per hour (20 instead of 12). This would be sufficient for Szeged for the 316 extra trains needed to be run. In this case RDSI = 0.786. Changing of SR_{tr} may be the least risky and the least costly option.

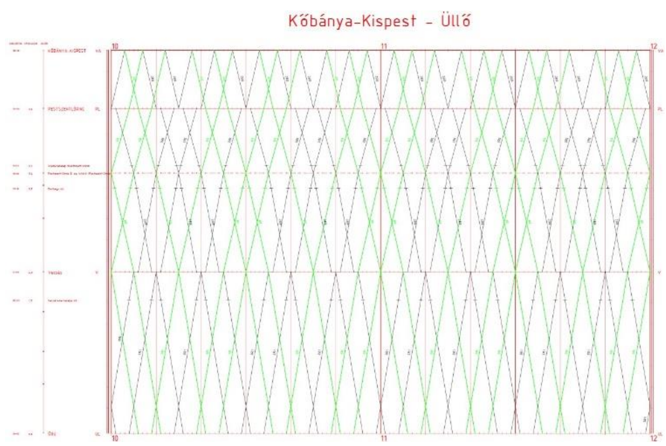

Figure 4. Extra trains with 5 minutes slot time (SR_{tr}) in the timetable diagram (RDSI = 1)

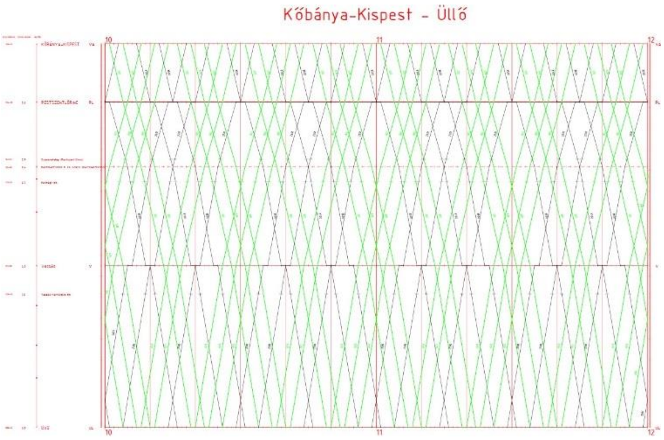

Figure 5. Extra trains with 3 minutes slot time (SR_{tr}) in timetable diagram (RDSI = 1)

5.4 Partial flexibility analysis

The partial flexibility analysis gives an idea of the protective utility of a railway line. The individual factors of the RDSI are expressed in numbers of train units; i.e., the partial elasticity analysis looks at the change in the value of each factor by 1 unit, namely, 1 train, which has an effect on the value of the index. In order to determine this, the possible discrete values of the change in each factor and the resulting change in the value of RDSI must be examined.

5.4.1 Change in the value of trains that can be run

The values in the denominator of the index are factors affecting transport safety. All four safety factors have an impact on the capacity of the line, but to different degrees.

The technical safety requirements (SR_{te}) define a technical level, the modification (upgrading) of which is not aimed at increasing the number of trains per 1 unit, but generally aims at achieving an increase of at least 10-15% in the number of trains, but in some cases doubled, for example adding the second track. Although technical improvements leading to an increase of 1 unit are theoretically possible, they are not common. Given the above, it can be stated in general that a change in the factor due technology advancements has a significant impact on the value of the index, but altering this factor is the costliest capacity-increasing procedure. Nevertheless, it is also true that its impact is long term.

A change in the operational safety requirements (SR_o) can be interpreted as a change for 1 train, because any technical equipment failure or malfunction can cause delays for only 1 train as well as for a significant number of trains. An increase in safety of operation by 1 train means that the number of trains not running due to a technical failure of the infrastructure is reduced by 1 train. Operational safety is further understood to mean, in particular, that the safety equipment must not allow any usage during its operation that could lead to an accident. Such a positive change in SR_o is reflected in a reduction in the number of incidents that have occurred, which can also be statistically interpreted as 1 unit. It follows that an improvement in safety of 1 unit only slightly changes the value of RDSI.

The Traffic Safety Requirement (SR_{tr}) is expressed in the number of accidents that have occurred and the resulting safety requirement is expressed in the additional number of train units that can be operated by the rules. In many cases, the definition of traffic safety rules is based on practical experience and measurements, but the way in which they are defined is left to the rule maker. The rules are characterized by a greater distance from the margin of error than in the field of technical or operational safety. For example, for standard gauge rail traffic in Hungary the rules allow a train following time of 5 minutes at most, while for other types of railways the same value can be as high as 80 seconds (with different safety technology of course), and in other countries (e.g., Austria and Switzerland) the minimum value for trains to follow each other is 3 minutes. The example shows that traffic safety rules can also cause a change in the value of the index, but that in other cases, replacing technical and operational safety factors with a traffic safety factor can significantly increase the human labor input and increase the risk of accidents by increasing the human factor.

The main purpose of the defense security requirements (SR_d) is to protect the infrastructure and ensure its operability. Each security solution contributes only slightly to the number of trains that can run, either positively or negatively (e.g., border gate operation), so that a change of 1 unit in the factor requires a significant level of security innovation and therefore this factor has less impact on the value of the index.

Overall, the technical security requirement is the most elastic factor, as it has the greatest potential to change the value of RDSI.

5.4.2 Changes in the value of the trains to be run

The number of trains to be run consists of two factors: trains according to the schedule and trains running in emergency cases. From the point of view of the index, it is necessary to start the investigation with the latter. In the event of extraordinary events, the running of these types of trains has priority over scheduled trains; i.e., if the denominator of the index cannot be changed immediately and a schedule capacity reserve proves to be insufficient, the traffic of scheduled trains must be cancelled in order to allow the trains needed in an emergency situation to be able to run. However, in a protracted emergency situation, it must also be considered that the transportation of manpower cannot be stopped by cancelling scheduled trains, because then the viability of the economy may be threatened. Therefore, it is worthwhile to examine the economic role of scheduled trains for each railway line. In order to identify the weak points of the railway infrastructure, I determined the relationship between RDSI and CI. When examining scheduled trains, this relationship must be used to determine how important these trains are in an emergency situation. In other words, the number of required regular trains is determined by:

- The type of the line (urban, commuter, main line, regional, etc.)
- The substitutability of a given line with other subsectors, which is expressed by CI based on RDSI of the railway line

It is necessary to note that in some cases, when increasing the number of trains to be run (for example, replacing passenger trains with buses) the demand for equipment and manpower may also increase significantly (i.e., buses and bus drivers).

It can be stated that the minimum number of trains, i.e., their weight, depends on the above factors, and in this case the weighting of the S_s factor has a right to exist. I recommend determining the weight numbers as follows:

- Metropolitan suburban line: 0.95
- Rural suburban line: 0.75
- Double-track main line: 0.6

• Single-track main line that cannot be replaced easily by bus: 0.6
• Single-track main line that can easily be replaced by bus: 0.5
• Single-track regional line that cannot be easily replaced by bus: 0.5
• Single-track regional line that can easily be replaced by bus: 0.3

With the partial flexibility analysis of RDSI, the conclusions regarding individual railway lines (station intervals) can be expanded with the role of the line in economic and social life. The weighting of the number of scheduled trains according to the type of the lines and the substitutability of trains (the ability to cancel running trains based on their role in economic and social life) can further specify the defense capabilities of a railway line. This is, therefore, even more important in determining the performance and resilience of the country. Changing the technical safety requirements through developments results in a gradual jump in the value of the index, which also has a significant impact on the protection ability of a railway line.

The partial felxibility analysis answers the question that the relationship between the security levels defined by RDSI and the incorporation of RDSI in the detour search method can increase a country's security of defense and resilience by showing possible detour routes, which are essential for a rapid crisis response, whether it is a terrorist attack, war or natural disaster.

5.5 Considering the effects of climate change

Climate change is one of today's threatening factors and it is necessary to protect against its harmful effects. This is also true for military operations, and one of the critical areas is maintaining the continuity of this supply chain [50]. Transport, as a sector that ensures the operation of the supply chain [51], is affected by the effects of climate change, because damage caused by extreme weather can affect the realization of relocation processes. Taking all this into account, it is a legitimate suggestion to examine the exposure of transport, and within that rail transport, related to climate change, as well as to display this in RDSI. According to the disaster risk assessment documents, the following natural events may affect traffic routes:

• Extreme weather
• Water damage
• Geological risks

Extreme weather events can also be further divided as follows:

• Sudden fall of a large amount of precipitation
• Stormy or hurricane-force winds (> 90 km/h)
• Extremely cold (< – 25°C) or extremely hot (> + 40°C) temperatures, cold or heat waves

Floods and inland inundation can be classified as water damage, earthquakes, landslides, soil erosion, and mass movements as geological risks. Based on the above, the effects of climate change can be incorporated into RDSI in two ways.

5.5.1 Incorporating the impact of the climate change based on empirical results

The investigation empirically analyses the extraordinary events that occurred on a given railway line as a result of extreme weather, the severity and the timing of the events, the duration of the prevention, the frequency of occurrence, and the possible protective measures. Based on this, in line with similar parameters, the possible protection measures must be selected, and the safety requirements must be specified. On this basis:

If the protection measure affects the track infrastructure: the SR_{te} value must be corrected
• If the protection measure affects the construction of other protection equipment: the value of the SR_o must be corrected
• If the protection measure means the adoption of rules: the value of the SR_{tr} must be corrected

The correction factors must be applied for a given line until the given protection measures are built or come into effect.

5.5.2 Incorporating the impact of the climate change based on model experiments

Due to climate change, extreme weather can also affect a railway line for which there is no experience value, because an extraordinary event attributable to weather has not yet occurred on that line. Anticipation of the impact of climate change in the future is possible by specifying characteristics based on the daily values of meteorological variables. These can be quantified using climate indices from regional climate model simulations [52]. Climate indices characterize the frequency of exceeding a given threshold value. Each index describes different weather effects, which can be of different intensity, and therefore common characterization is difficult due to the different probability distribution of each weather variable.

Hence, it is recommended to conduct a regional investigation of the individual effects of different climate parameters based on regional climate model simulations in the region where a given railway line is located, and then to create a complex, multidimensional climate index, similar to the Climate Extremes Index (CEI) [53]. The multidimensional climate indicator shows which area (territorial percentage) of the country is affected (in the future) by an extreme climate event that has a negative impact on rail traffic. Management of uncertainties is possible based on several models and several emission scenarios.

The safety and security requirements based on the regional weather indices for the given area must be primarily included in the technical requirements, so that a suitable technical protection procedure can be developed for a given weather extremity. Until the installation of the technical solution, it is recommended multiplying the technical safety requirements by a correction factor ξ calculated on the basis of the multidimensional climate index, which reduces the number of trains that can be run, because it is necessary to expect such an extreme weather effect that can limit or, where appropriate, make train traffic impossible.

The RDSI is suitable for demonstrating the ability to resist climate change, if the scope of the definition of the technical safety requirements (SR_{te}) is expanded with the ξ correction factor formed from the multidimensional climate index. The climate index determines the expected extreme weather effects, with which the capacity calculated on the basis of the technical safety requirements must be reduced. The emergence of technical responses to climate change challenges in the technical safety requirements can again increase the capacity of a given line. With this method, the RDSI is suitable for assessing the resilience of the railway network against climate change and for determining the necessary level of protection.

The use of RDSI and its combination with meteorological climate models, can help to avoid the impact of (sudden) changes in weather conditions due to climate change on rail transport by determining the weak points of the infrastructure. With targeted improvements of these, the whole rail sector will become more robust and this could be a further implication for the transport safety and defense security of rail transportation.

6. CONCLUSIONS

The challenges of everyday life make it necessary to increase the safety of transport systems. This means protecting both human lives (from society aspect) and infrastructure (from military aspect) at the same time. The article deals with the solution of this dual task.

The Railway Defense Security Index (RDSI) developed by this theoretical research, shows the defense reserves of a given railway line and highlights the need for infrastructure developments for defense purposes. From a traffic and civil-military point of view, the index determines the extent of defense capacity reserves the given railway line has in proportion to the defense security requirements, so it is suitable for underpinning the need for infrastructure investments for railway defense and measures to improve transport safety. The use of this evaluation index can be an important parameter for the development of military defense security and civilian transport safety systems, so this novel method improves the defense security of the railway sector.

From the examination of the transport and defense safety system, it can be concluded that the joint application of the systems has a mutually reinforcing effect, that is, the safety of rail transport can be increased to a greater extent. Based on the research results it can be the concluded that this mutually reinforcing effect is of decisive importance in determining the tasks of preparedness for protection and security. The novel method with the usage of RDSI can be considered as part of the requirement model [54] for complex security preparedness of railway infrastructure systems.

The research results of the article can create great opportunity for thinking together in transport planning and defense preparation (see as in [10]). Defense security tasks must appear in transport development plans.

Based on the research results the relationship between rail transport safety and defense security was determined, as well as the RDSI, which measures the level of rail security. The index can be used to identify the infrastructure investments needed to achieve defense security, which can significantly improve a country's resilience. By incorporating the index into the detour search methodology and combining it with meteorological climate models, further implications for rail transportation can also be achieved. Thus, the research questions are answered.

The results are primarily used to prepare for protection against deliberate human actions, but destruction and damage can be caused not only by terrorists or soldiers, but also by natural influences and careless human behavior. So, the research results can therefore be used in the fields of disaster management as well.

The extreme weather conditions of the past period have in many cases tested the ability of professionals in the transport sector, and in particular in the rail sub-sector, to organize adequate replacement. The research results can provide an appropriate basis for developing the necessary scenarios and emergency replacement solutions. The results of this paper can give an answer 'yes' to the Dutch researchers' question that the well-functioned railways can make freight transport more resilient, but there is a consensus that this requires significant developments [55].

Therefore, although the rules for rail transport are specific, the index, the concept and criteria developed in this research can be able to identify the necessary protection measures for other transport sub-sectors and critical infrastructure sectors.

The application of the requirement model to the task of transport support, defined as part of military logistics within defense science, contributes to the effectiveness of defense preparedness. This will significantly increase the efficiency of the military forces in the performance of their defense tasks and helps to solve the following problems:

- Public safety and security
- Environmental protection and climate change
- Disaster risks
- Terrorism prevention

In addition, road-rail crossings as critical point protection solutions may be an area of research where the thread of the evaluation index can be taken further. Increasing the level of safety in this area can both further enhance the success of preparedness for protection and bring about a significant increase in road safety standards, which can be most visible in terms of lives saved.

Safety index can be determined not only for railway infrastructure, but also for vehicles and personal safety. Based on the results of this research, these may represent future research directions with a focus on cyber security, blockchain and AI.

At the same time, further research is necessary for the determination of the multidimensional climate index developed in this article, and its correlation with the transport sector.

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NOMENCLATURE

RDSI	Railway Defense Security Index
N_s	Number of regular (scheduled) trains, pcs
N_e	Number of trains running in an emergency situation, pcs
SR_{te}	Technical safety requirements, (train) pcs
SR_o	Operational safety requirements, (train) pcs
SR_{tr}	Traffic safety requirements, (train) pcs
SR_d	Defense security requirements, (train) pcs
w_t^*	Travel time edge weight modified by security requirements, min.
w_t	Travel time edge weight
w_ℓ^*	Path length edge weight modified by security requirements
w_ℓ	Path length edge weight
CI	Concurrency Index
CI_s	Concurrency Index of the substitute line
S_t	Score of travel time, pts
S_s	Score of schedules, pts
q	Substitution threshold
j_s	Journey time on the substitute route, min.
j_o	Journey time on the original route, min.
$RDSI_s$	Railway Defense Security Index of the substitute line
NATO	North Atlantic Treaty Organization
UIC	International Union of Railways (Union Internationale des Chemins de fer)
CEI	Climate Extremes Index
ξ	Safety requirement correction factor
AI	Artificial Intelligence