

PRACTICAL APPLICATION OF A MODEL FOR ASSESSING THE CRITICALITY OF RAILWAY INFRASTRUCTURE ELEMENTS

Petr NOVOTNÝ¹, Jiří MARKUČI², Michal TITKO³, Simona SLIVKOVÁ⁴, David ŘEHÁK⁵

Research article

Abstract: Rail transport is an important sub-sector of transport infrastructure. Disruption of its operation due to emergencies can result in a reduction in functional parameters of provided services with consequent impacts on society. Identification of critical elements of this system enables its timely and effective protection. On that ground, the article presents a draft model for assessing the criticality of railway infrastructure elements. This model uses a systems approach and multicriteria semi-quantitative analysis with weighted criteria for calculating the criticality of individual elements of the railway infrastructure. In the conclusion, it presents a practical application of the proposed model including the discussion of results.

Keywords: Critical infrastructure, criticality assessment, railway infrastructure, systems approach, model.

Introduction

Railway transport network can be considered an important part of the technical infrastructure of developed countries (Johansson, 2011). Some sections or nodes represent a significant parts of the railway network. In some cases, these elements can be so significant that their destruction or failure, as a result of the impact of hazardous events, can cause serious effects on the performance of the basic functions of the state (or region) and may thus compromise also their safety (Lewis, 2006). Such elements are then designated as elements of railway critical infrastructure.

The process of inclusion of specific elements of the rail infrastructure among critical elements requires an assessment of the criticality of such elements (Eismann, 2014). The assessment of the criticality of railway infrastructure components can be carried out on the basis of different approaches (Slivoně, 2008). In its inner essence, the railway transport is a standalone system; by external links, however, it is also more or less interconnected with other systems (Hokstad, 2015). For this reason, when assessing the criticality of the railway transport infrastructure, it is necessary to consider

system linkages. The authors therefore recommend a systems approach for criticality assessment that respects the interaction between different systems.

Elements of any infrastructures cannot form a working system without linkages and flows between them (Trucco, 2014). As a whole, the system(s) consisting of these linkages and flows between them exhibits (exhibit) certain characteristics over time and in the respective space (Procházková, 2012). Certain features of behaviour can be described as they are constant over time and in a specific space (O'Rourke, 2007). Relationships with the surrounding are crucial for the integrity of the system (as well as its function). All the above-described properties can be found also in infrastructure systems including critical infrastructures (Jönsson, 2008).

Materials and methods

Properties of infrastructure systems change over time; therefore, it seems appropriate to designate these critical infrastructures as complex dynamic structures. However, even dynamic structures do not show unlimited capacity for adaptability (Trucco, 2014). Based on this, it is necessary to detect weaknesses which reduce the adaptability

¹ VŠB - Technical University of Ostrava, Faculty of Safety Engineering, Ostrava, Czech Republic, novotny.petr@vsb.cz

² VŠB - Technical University of Ostrava, Faculty of Safety Engineering, Ostrava, Czech Republic, jiri.markuci@vsb.cz

³ University of Žilina, Faculty of Security Engineering, Žilina, Slovak Republic, michal.titko@fbi.uniza.sk

⁴ VŠB - Technical University of Ostrava, Faculty of Safety Engineering, Ostrava, Czech Republic, simona.slivkova@vsb.cz

⁵ VŠB - Technical University of Ostrava, Faculty of Safety Engineering, Ostrava, Czech Republic, david.rehak@vsb.cz

of the system. To ensure the reliability and stability of the system, we must find threshold values for operational stability and reliability of the individual components, i.e. the criticality (Procházková, 2012). The notion of element criticality can also be understood as a system property which defines its difficult (or impossible) substitutability as well as the impact on the entire system in case of functional failures of such element (Egan, 2007). Criticality assessment is therefore based on the principle of systems approach to the issue of critical infrastructure protection. Criticality assessment is also one of the main parts of the proposal for a systems approach to identifying critical infrastructure in those European countries which do not have a systems approach so far (Novotny, 2015). Detection of weaknesses in the system (criticality of individual elements) uses methods of multi-criteria analysis (Heimes, 2002) which allows a focus on evaluating the failure of one element or a set of several elements of the system. The criticality analysis can be carried out on the basis of selected criteria. These criteria characterize the basic properties of elements considered (relevant to all elements of the system) while taking into account the effects of malfunctioning on other systems (Procházková, 2012).

For the purpose of implementing a practical application, a failure of one element has so far been considered. Based on assessing the degree of criticality of the individual components of the system, it is possible to identify critical elements and consequences that could be caused by their failures. Within the proposed model, it is also possible to sort the assessed critical elements according to the preferences of responsible entities (Johansson, 2011). Assessing the criticality of the elements of the railway infrastructure is the content of the draft model that considers the specifics of the actual railway infrastructure on one hand, and applies the principles of systems approach and takes into account possible interactions in the system on the other hand. The proposed method examines multiple dimensions of criticality (Rinaldi, 2001) and uses weighted criteria to determine the degree of criticality, characterizing important features of the railway infrastructure.

Criticality assessment model

This part of the article describes the model used for assessing the criticality of the railway network elements system (see Fig. 1) which respects to the guidelines of risk management according to ISO 31 000 (ISO, 2009). Therefore, the activities are implemented in the following sequence: establishing the context, identification of the infrastructure

elements, analysis of criticality of the elements and, finally, its evaluation. Monitoring and reviews must be conducted throughout the process as well as communication and consultations with experts during the subsequent practical application. The entire process takes place continuously and activities divided into some activities may obviously overlap.

Establishing the context of assessing the criticality of the elements of the railway infrastructure is divided into internal context (matters concerning the railway infrastructure only) and external context (having ties outside the railway infrastructure alone). The subsequent criticality assessment requires the identification of all the elements of the comprehensive infrastructure system (or comprehensive part of the infrastructure). For the elements identified for the analysis of railway infrastructure, the following classification can be used:

- Nodes (which consist of the following elements):
 - railway stations,
 - at-grade intersections (railway branches, railway crossings),
 - grade-separated intersections (road and rail overpasses and underpasses).
- Connections (between individual nodes) which may be formed by:
 - common sections,
 - tunnels and bridges (not grade separations).

In the above-identified elements, it is necessary to analyse the respective dimensions of interdependencies (Rinaldi, 2001) within the internal and external contexts. For the assessment of criticality, it is essential to realize mutual close association of different dimensions of criticality within the internal and external context of criticality assessment and adapt the context definition to this fact. Within the proposed model (see Fig. 1) for the railway infrastructure, it is advisable to analyse three key dimensions: physical, geographic and social (Rinaldi, 2001). The social impact is determined by economic and well-being impact to society. Cyber dimension (Rinaldi, 2001) is not reflected in this proposed model due to fragmentary data. Absence of the cyber dimension does not cause decreasing of model application. In this way, it is possible to implement the issue of interdependencies and systems approach into the criticality assessment process.

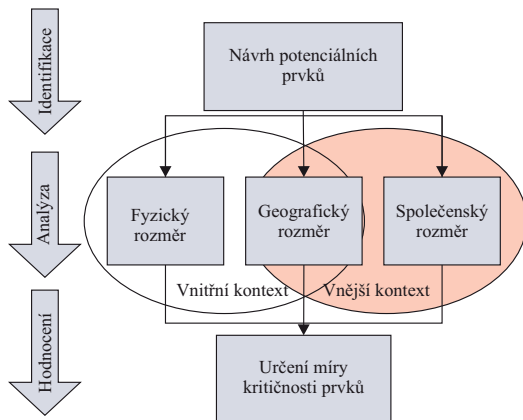


Fig. 1 Model for assessing the criticality of railway infrastructure elements

In order to maintain consistency of the approach for all elements identified above, it is necessary to analyse the various dimensions of criticality on the basis of appropriate criteria which take into account the specificities of particular elements while providing relevant results.

Resulting criticality of elements

The final assessment of the criticality of railway infrastructure elements is based on the relationship between the physical, geographic and social dimensions. Consultations (Červenka, 2015) led to establishing a steady relationship between the criteria and the final formula for calculating the criticality of railway infrastructure elements is presented by relationship 1.

$$C_{Ei} = \frac{C_{PDi} + C_{GD_i} + C_{SD_i}}{3}$$

for all $i \in N(1)$

where C_{Ei} = criticality of the i -th element; C_{PDi} = physical dimension of the criticality of the i -th element; C_{GD_i} = geographical dimension of the criticality of the i -th element; C_{SD_i} = social dimension of the criticality of the i -th element.

The resulting criticality (as well as the individual dimensions) may also take the values from 1 to 5 whereas the lowest and highest possible levels of criticality are 1 and 5, respectively. For this reason, a uniform scale was selected for the individual levels of criticality (Červenka, 2015) and individual elements were classified in categories of criticality. Generally, the degree

of criticality for each element can thus take values according to the relationship 2.

$$C_{Ei} = \left\{ C_{E_{\min}} ; S \cdot \frac{C_{E_{\max}} - C_{E_{\min}}}{n} \right\}$$

for all $S \in \langle 1 ; n-1 \rangle, i \in N(2)$

where C_{Ei} = criticality of the i -th element; $C_{E_{\min}}$ = minimum value of criticality; $C_{E_{\max}}$ = maximum value of criticality, n = number of levels of the selected scale.

Based on the above method of calculating the criticality of infrastructure elements, it is possible to process larger volumes of data and then use the results obtained to create additional procedures in the field of the critical infrastructure protection, particularly the railway infrastructure.

Physical dimension

Analysis of the physical dimension of element criticality consists in assessing the importance of the elements within the railway network. Similarly, it is used in determining the systems importance of the element (Rostek, 2014). This analysis aims at analysing the importance (status) of the elements within the railway infrastructure in question. The importance of each element is determined by criteria that fundamentally affect the actual assessment and which include:

- costs of restoring the element ($C_{PDi(RC)}$),
- replaceability by railway ($C_{PDi(RR)}$),
- significance of the railway section (railway type) - international corridor, national or regional railway ($C_{PDi(RT)}$).

After consultations with the railway infrastructure operator (in the Czech Republic, the leading operator is the Správa železniční dopravní cesty, státní organizace - hereinafter also referred to as "SŽDC, s.o."), weights were assigned to each criterion (Červenka, 2015). The weights for each criterion were calculated using the Fuller method (Fotr, 1988) and are given in Tab. 1.

Tab. 1 Determination of weights for the physical dimension of criticality according to the Fuller method (Fotr, 1988; Šenovský, 2015)

Comparison of criteria		Criterion	Appearance	Modified Appearance	Ranking	Criterion weight
$C_{PDi(RC)}$	$C_{PDi(RC)}$	$C_{PDi(RC)}$	2	3	1	3/6
$C_{PDi(RR)}$	$C_{PDi(RT)}$	$C_{PDi(RR)}$	0	1	3	1/6
		$C_{PDi(RT)}$	1	2	2	2/6

Based on the above criteria and their determined weights, the final degree of the physical dimension was calculated according to relationship 3.

$$C_{PDi} = \frac{3}{6} \cdot C_{PDi(RC)} + \frac{1}{6} \cdot C_{PDi(RR)} + \frac{2}{6} \cdot C_{PDi(RT)}$$

for all $i \in N$ (3)

where C_{PDi} = physical dimension of criticality of the i -th element; $C_{PDi(RC)}$ = costs of restoring the i -th element; $C_{PDi(RR)}$ = replaceability of the i -th element by railway; $C_{PDi(RT)}$ = character of the track (railway type) of the i -th element.

The criterion of substitutability (replaceability) by railway is logically composed of two factors: the length of the diversion route ($C_{PDi(RRdl)}$) and the quality of the diversion route ($C_{PDi(RRdq)}$). In this criterion, based on consultations with SZDC, s.o., weights were also assigned to these factors, according to relationship 4a.

$$C_{PDi(RR)} = \frac{1}{2} \cdot C_{PDi(RRdl)} + \frac{1}{2} \cdot C_{PDi(RRdq)}$$

for all $i \in N$ (4a)

where $C_{PDi(RR)}$ = substitutability of the i -th element by railway; $C_{PDi(RRdl)}$ = length of the diversion route for the i -th element; $C_{PDi(RRdq)}$ = quality of the diversion route for the i -th element.

The resulting degree of the physical dimension of criticality of railway infrastructure elements can take values from the range between 1 and 5 whereas the values of 1 and 5 represent the lowest and highest degree of physical dimension, respectively.

Geographic dimension

Analysis of the geographic dimension of element criticality includes intersections with roads (e.g. overpasses and underpasses) in line structures, and connections to other railway lines and road network (stops, stations, transit sheds) in nodes. Regarding the geographic dimension of element criticality, it is important to properly evaluate the nature of connection or significance of intersections between the given infrastructures. The geographic dimension is therefore described by a relationship valuating the criteria of significance for individual intersecting infrastructures, i.e. the following criteria:

- importance of the intersected infrastructure - road network infrastructure ($C_{GDi(RO)}$),
- importance of the intersecting infrastructure, always the railway infrastructure ($C_{GDi(RA)}$).

After consultations with SŽDC, s.o., the weights for the above criteria of the geographic dimension of criticality of railway infrastructure elements were determined according to relationship 4b.

$$C_{GDi} = \frac{1}{3} \cdot C_{GDi(RO)} + \frac{2}{3} \cdot C_{GDi(RA)}$$

for all $i \in N$ (4b)

where C_{GDi} = geographic dimension of the i -th element; $C_{GDi(RO)}$ = significance of the road intersecting the i -th element; $C_{GDi(RA)}$ = significance of the railway in the i -th element.

The examined model is limited by the availability of information about intersected infrastructures. This model thus takes into account only intersections with the road infrastructure, mainly due to possibilities of incidents (overpasses, underpasses, bridges) and resulting traffic restrictions. It does not consider, for example, intersections with technical infrastructures (pipelines, power grids, etc.), which would obviously not detract the model functionality in any way.

The resulting degree of the geographical dimension of criticality of railway infrastructure elements can also take values from the range between 1 and 5.

Social dimension

The social dimension of criticality of railway infrastructure elements is characterized by impacts on society represented by people using the rail transport services (i.e. “transported persons”, simply said). Based on consultations with the operator (Červenka, 2015), the following criteria of the social dimension have been selected:

- passenger traffic intensity ($C_{SDi(TI)}$),
- time of restoring the passenger transport ($C_{SDi(TR)}$),
- alternative transport level ($C_{SDi(AL)}$).

The weights for each criterion were again calculated using the Fuller method (Fotr, 1988) and are given in Tab. 2.

Based on the above criteria and their determined weights, the final degree of the social dimension was calculated according to relationship 5.

$$C_{SDi} = \frac{3}{6} \cdot C_{SDi(TI)} + \frac{2}{6} \cdot C_{SDi(TR)} + \frac{1}{6} \cdot C_{SDi(AL)}$$

for all $i \in \{1; \infty\}$ (5)

where C_{SDi} = social dimension of the criticality of the i -th element; $C_{SDi(TI)}$ = passenger traffic intensity in the i -th element; $C_{SDi(TR)}$ = time of restoring the passenger transport in the i -th element; $C_{SDi(AL)}$ = alternative transport level for the i -th element.

Tab. 2 Determination of weights for the social dimension of criticality according to the Fuller method (Fotr, 1988; Šenovský, 2015)

Comparison of criteria		Criterion	Appearance	Modified Appearance	Ranking	Criterion weight
$C_{SDi(TI)}$ $C_{SDi(TR)}$	$C_{SDi(TI)}$ $C_{SDi(AL)}$	$C_{SDi(TI)}$	2	3	1	3/6
	$C_{SDi(TR)}$ $C_{SDi(AL)}$	$C_{SDi(TR)}$	0	1	3	1/6
		$C_{SDi(AL)}$	1	2	2	2/6

After consultations with SŽDC, s.o., the weights were assigned also to both factors in the criterion of replacement transport level, equally according to relationship 6. This criterion is composed of two factors: time loss due to the replacement transport and the need for replacing the train connection with an alternative bus transportation.

$$C_{SDi(AL)} = \frac{1}{2} \cdot C_{SDi(ALtd)} + \frac{1}{2} \cdot C_{SDi(ALda)} \quad (6)$$

where $C_{SDi(AL)}$ = alternative transport level for the i -th element; $C_{SDi(ALtd)}$ = time delay due to the replacement transport for the i -th element, $C_{SDi(ALda)}$ = demand for the alternative transport for the i -th element.

After determining the weights for criteria of the social dimension of criticality, it is possible to calculate the degree of the social dimension of criticality of the railway infrastructure element that can also take values in the range from 1 to 5.

Results and discussion

After the calculation of the criticality of railway infrastructure elements, i.e. nodes and connections, the criticality of individual elements can be classified into appropriate categories of criticality according to relationship 2. Based on the calculation, however, it appears prudent to set out a limit value of the degree of criticality for the implementation of subsequent measures. The limit value is represented by the low level of criticality (as calculated, it is the degree of criticality from the value of 2.6). This value was determined after mutual consensus with the railway infrastructure operator. The responsible authority should then determine which categories of criticality (low, medium, high) will be primarily addressed when protecting the railway infrastructure elements.

Practical application of the proposed model for assessing the criticality of railway infrastructure elements was carried out on the territory managed by the SŽDC, s.o., the regional Directorate in Ostrava (i.e. approximately the territory of the Moravian-Silesian Region). For this practical application, the organization provided data for railway nodes

(stations) and railway sections between the nodes. Individual nodes are numbered from 1 to 35. The section between points 1 to 20 (Čadca - Bohumín) is an international corridor and other nodes with connecting sections (21 to 35) represent possible diversion routes in case of failure of the international corridor or just another nodes in the territory, not evaluated in terms of their significance (in purple). Rated sections and nodes are highlighted in yellow, orange and red, as shown in Fig. 2.

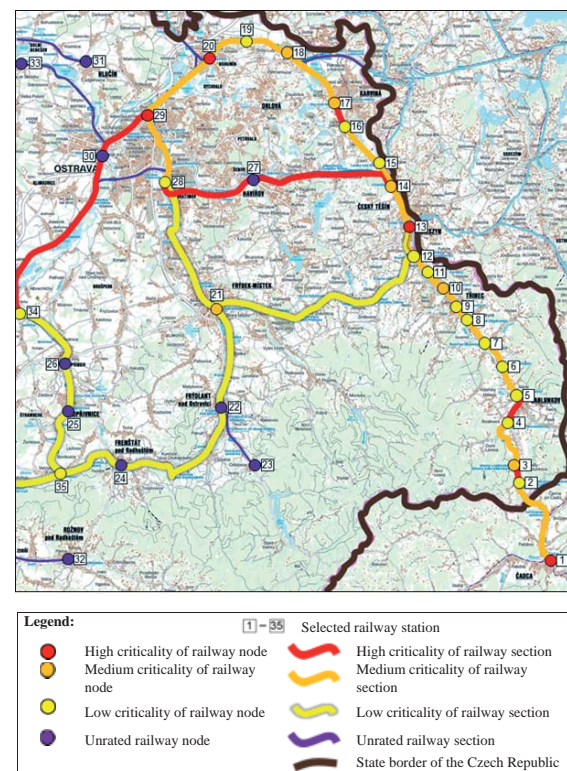


Fig. 2 A graphical representation of the degree of criticality of railway nodes and sections

On the basis of colour discrimination, it is possible to identify a high, medium and low criticality of railway sections and nodes. High criticality of some elements may be caused by multiple factors. It can be concluded that railway sections (connections) mostly represent an irreplaceable element in the relevant section, which could not be replaced in the case of damage or malfunction. For example, the irreplaceable element can be a tunnel with a length of 600 metres, located in the section between points 2 and 3. In contrast, the section between points 4 and 5 contains an at-grade intersection between the international railway corridor and primary road. This intersection of infrastructures (railway crossing) also

caused an increase in the degree of criticality for this section. The two aforementioned sections are therefore classified as sections with high criticality since there is no diversion route in the territory of the Czech Republic.

Another section with a high level of criticality is located between points 14 and 28. In this case, the degree of criticality is increased by a large number of overpasses, underpasses and bridges appearing on this route. Restoration of this section may be significantly limited in the event of damage to the above mentioned elements. Grade-separated intersection with the primary road, longer time required for the replacement bus transportation and very long bypass route for the short section between points 16 and 17 can also contribute to a higher degree of criticality. A similar situation occurs in the section between points 29 and 34, including a grade-separated intersection with the highway, very long diversion route and many overpasses, underpasses and bridges. Restoration of this section would be really very difficult. In most cases, a decisive factor for railway nodes was the geographical dimension of the criticality of railway nodes, as in the case of nodes 1, 13 and 20, located close to a major road (highway, high-speed road). In contrast, the degree of criticality in node 29 is mainly increased due to its importance and extent.

It should be noted that the mean value of the criticality of sections and nodes is not surprising, since these are elements situated mainly in the international corridor. The processed graphical representation of the degree of criticality of railway infrastructure elements can also provide plenty of other useful information. Comprehensive graphical output can also be used to plan and prioritize appropriate measures for the protection of railway infrastructure elements.

Conclusion

Application of thus proposed system model for assessing the criticality of railway infrastructure elements can be beneficial especially in terms of the inclusion of internal and external context. Another benefit of the model can consist in considering the interconnection of elements as well as other infrastructures. The proposed approach leads to 'a more accurate identification of critical elements of the railway transport infrastructure on a large scale. This is due to the fact that it includes the importance for the railway infrastructure itself (physical dimension) as well as the importance of interdependent infrastructures (geographic dimension) and, last but not least, also social impacts (social dimension). A benefit of conducting the criticality analysis by the above-proposed method is

the possibility of its application in a semi-quantitative way with the help of multi-criteria analysis using weighted criteria (this gives a space for applying the preferences of responsible entities). The resulting evaluation of criticality for various elements of the railway infrastructure can be represented graphically or by numerical values, depending on the required output. The most difficult phase of the analysis implementation is the valuation of individual criteria; in this stage, the greatest distortion of analysis results may happen. Nevertheless, the subjective distortion can be prevented by involving more assessors from different interested stakeholders (risk management, railway transport, road transport, social sciences, etc.).

Currently, the issue of assessing the criticality of the elements of large-scale infrastructures is the interest of academic community as well as professionals in practice. The result of this proposal represents a real interconnection of these interests because the outputs of the proposed assessment of the criticality of railway infrastructure elements will be further applied in the preparation and planning of population protection measures in relation to the issue of passenger transport via railways.

A systems approach to the issue of assessing the criticality of railway infrastructure elements allows us to consider all relevant facts related directly to the operability of the given infrastructure. In addition, this approach enables the user to take into account the essential interdependences with other elements and systems; therefore, it represents an appropriate method for evaluating the criticality of elements. The proposed procedure can also be applied at a nation-wide level for selecting nationally important elements that will be most critical in terms of railway infrastructure. At the same time, however, it is also necessary to consider the demands on processing real data that are needed to implement the criticality analysis on a large scale. Due to its design, the given model can be transferred into software environments; this can streamline decision-making processes of the responsible authorities.

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