Integral approach to assessing the criticality of railway infrastructure elements

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Abstract: In the last ten years, considerable attention has been paid to analysing and assessing the criticality of railway infrastructure elements. Publications on the subject mostly assess elements only from a certain point of view, such as purpose, reliability or risk. This leads to only a partial assessment of criticality without continuous correlation, which may result some critical elements of the system being omitted. The article introduces the railway infrastructure criticality assessment tool (RICA tool), which was created to evaluate the criticality of railway infrastructure elements in all aspects. The integral approach of the tool lies in comprehensively assessing the technical and process factors of rail transport. The criticality of railway infrastructure elements is therefore assessed not only in terms of the relevance and resilience of elements but also their interdependence, substitutability, risk and impact.

Keywords: railway infrastructure; criticality assessment; integral approach; RICA tool; technical and process factors.

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1   Introduction

Rail transport is one of the most important modes of transport on land for people and freight. Its importance is emphasised, inter alia, under the North Atlantic Treaty Organisation (NATO), in which it forms one of the supporting means of transport for armed forces (Vlkovsky et al., 2017). Because of their importance and high impact at a social, economic, psychological and political level, transport systems are often key targets for terrorist attacks (Hedel et al., 2018). Based on the above, rail transport was included in the European Critical Infrastructure sectors in 2008 (European Council, 2008). In the following period, EU member states began identifying and determining the various elements of railway critical infrastructure at European and national levels (Rehak et al., 2016). The results of the assessment showed that in addition to elements of critical infrastructure, some elements did not meet the defined cross-sectoral and sectoral criteria in railway infrastructure but were key or even critical to the region (Slivkova et al., 2018). These elements must be appropriately identified, and their criticality evaluated in order to adopt adequate security measures (Leitner et al., 2017).

Current research provides a series of approaches to identifying critical elements. These approaches are not only of a general nature but also focus specifically on transport. General approaches are aimed either at systemic determination of infrastructure criticality (e.g., Katina and Hester, 2013) or at assessing the criticality of elements in different types of infrastructures by using a variety of factors. These factors include the possible impact of an element's failure on the assessed system (e.g., Jönsson et al., 2008; Luiijf et al., 2003), the dependence of the monitored element (e.g., Fekete, 2018; Rinaldi et al., 2001), the significance of the element (e.g., Alsubaie et al., 2015; Zhang et al., 2015), the vulnerability of the element (e.g., Pant et al., 2016; Theoharidou et al., 2009) and risks in relation to the element of interest (e.g., Dvorak et al., 2017; Pant et al., 2015; Sousek and Dvorak, 2013). Another important factor is assessing the criticality of elements from the perspective of the attacker, whose aim is to disconnect a network at a number of critical nodes and disrupt the connection of individual key components to other elements (Faramondi et al., 2016). A similar approach is assessing criticality by considering the risk of terrorist attack with the aim of optimally allocating limited resources for protection (Norkin et al., 2018). Most general approaches are usable as suitable input for an integral approach design to assess the criticality of railway infrastructure elements, but their direct use in such assessment is not possible.

By contrast, specific approaches are already based on the assessment of transport elements, but always from a certain point of view, which makes it impossible to achieve an integrated assessment. These approaches include, for example, identifying critical elements by calculating the increased cost of disruption to or delay in the element (Bababeik et al., 2017; Khaled et al., 2015). Assessing elements in terms of railway transport renewal according to a multi-criteria analysis of the financial, economic and environmental domains is a similar approach (Caetano et al., 2018). Another specific approach is assessing the importance of a given element (i.e., performance or category) or its importance arising from the possibility of an alternate route or the likelihood of occurrence of an adverse event (Leitner et al., 2017). Another aspect not to be overlooked is identifying critical sites based on reliability analyses (Fourie and Zhuwaki, 2017), analyses of expected accident data (Striegler et al., 2012) or analyses of the vulnerability of interdependent technical infrastructures (Johansson et al., 2011).

Based on the analysis performed it can be stated that these approaches are functional (although their application in most cases is difficult and/or difficult to comprehend) but they do not facilitate an integral assessment of elements, which is required for comprehensive assessment (CRIA, 2016). Against this background, the article introduces the railway infrastructure criticality assessment tool (RICA tool), which was developed to assess the integrity of critical infrastructure elements. The purpose of this assessment tool is to identify the critical railway infrastructure elements in a given territory for which measures can be subsequently established to ensure the preparedness or enhancement of resilience of designated elements (e.g., Rehak et al., 2018; Stoller et al., 2018; Klein and Hutter, 2017; Hromada and Lukas, 2012; Dvorak et al., 2013).

Criticality in the context of this article is seen as the relative measure of importance and meaning of a given element that also expresses the vulnerability of the element and the possible negative effects of its failure with regard to the links in the system. The integral approach of this tool lies in comprehensively assessing the technical and process factors of rail transport. The criticality of railway infrastructure elements is thus assessed not only in terms of the relevance and resilience of elements but also includes an assessment of their interdependence, substitutability, risks and impact.

2   Key factors determining and influencing criticality assessment

In general, any system can be comprehended as a group of interconnected and interactive elements that fulfil clearly defined tasks with varying material levels. The functioning of such a system is determined and influenced by a number of factors. Technical factors (i.e., infrastructure) and process factors are key factors that determine or affect system processes (Rehak et al., 2018). In the rail transport system, process factors include rail transport operators, transport processes, infrastructure links, active threats to the system and the impact of disturbing that system.

2.1   Technical factors

The basis of secure and high-quality rail transport is reliable infrastructure. It consists of railway estates, railway bodies, switches, other engineering constructions (e.g., bridges, tunnels and railway crossings) and associated station infrastructure (e.g., platforms, railway signals). These railway infrastructure elements are classified in three groups according to their topological structure, namely line elements (LEs), point elements and areal elements (AEs) (Rehak et al., 2019; Fekete, 2018).

LEs provide transfer, delivery or transport between two physically separate locations (i.e., connectors of individual elements/locations). They are a meaningful basic group in relation to all point and AEs. In railway transport, LEs are the individual lines.

PEs are closed units that fulfil their function for the needs of a particular LE. Mainly, these are locally defined points based in a small area. The PE can also work for several LEs (e.g., a diverging set of switches, diamond crossing with slips). Inside the railway infrastructure area, PEs are primarily railway equipment (e.g., communication equipment, railway signals, electrical equipment, signalling systems, switch systems), track construction, railway crossings and halts.

AEs are characterised as a whole unit and include places where multiple point and LEs can work simultaneously and where the very existence of so many elements in one place can be critical. AEs are the most complex group of elements, consisting of at least two PEs and at least one LE. In AE, the effects of an outage can accumulate. Mainly railway junctions, crossing protections and railway stations with railway signals form this type of element.

2.2   Process factors

An important variable in an integral assessment of the criticality of railway infrastructure elements are process factors. These factors partly determine, but primarily influence, the level of relevance and resilience of the assessed elements in the rail transport system. By integrating them into the assessment process, more accurate and comprehensive results are obtained on the criticality of each element and their interdependence. An overview of the process factors determining and influencing the criticality assessment of railway infrastructure elements is presented in Figure 1.

Each system is determined and simultaneously influenced by entities that either produce or use the service within that system or affect its operation in other ways (e.g., an authorised representative of the given system). Each of these entities enters the rail system with a different target and role in terms of the functioning of the entire system. The most important entities determining or affecting the railway system include:

- a managing authority (i.e., the Ministry of Transport) – function as an authorised representative in the transport sector

- inspection and investigative bodies (i.e., access to transport infrastructure authority, state rail authority, railway inspectorate) – regulatory, controlling or investigative functions in the transport sector

- rail operators – fulfilment of obligations, such as ensuring railway serviceability and safety, maintaining and repairing railways, or modernising and developing rail transport routes

- rail transport operators – operation of rail transport as a subject of business

- transport order parties (i.e., freight forwarders and passengers in passenger transport) – may have service requirements (transport) such as time, safety or qualitative requirements, require provision of transport services in a given territory.

The above-mentioned requirements of some rail transport operators may coincide at a certain point. The basic requirements of these entities are presented in Table 1.

Transport as such is strongly determined by transport processes that, in common harmony and logical continuity, contribute to the proper functioning of the whole system. Individual railway transport processes are a key foundation for fulfilling expected rail transport functions. Processes in rail transport can be divided into local processes for securing traffic in stations and network processes for securing traffic in the railway network (Gasparik and Kolar, 2017). Traffic security (transport safety), track management, rail transport organisation (shifts, delays, overtaking, etc.) and emergency measures (Ministry of Transport, 2013) are most often applied in the field of transport processes (Ministry of Transport, 2013).

Figure 1 Process factors determining and influencing criticality assessment
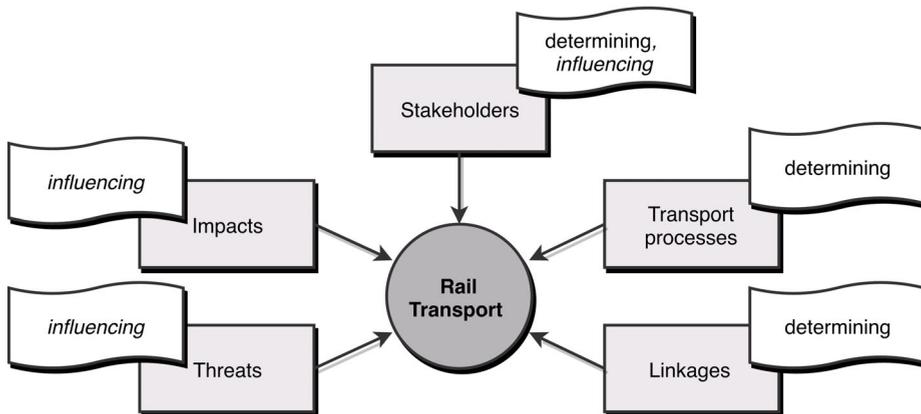
Another important determinant of each system is its linkages, which can be physical, cyber, related to geographic, or logical in nature (Rinaldi et al., 2001). The most important physical linkage in the rail transport system is the dependence of railway infrastructure elements on the supply of electricity. The most important cyber linkage considered can be the transmission of traffic management data and operation of transport systems (e.g., railway signals). Geographical linkages can be seen in terms of

the territorial distribution of individual lines and stations to provide connections and ensure transport serviceability of the region. The most important logical linkage in rail transport can be seen in the relationship between the rail operator and the rail transport operator. Without logical cooperation between these entities, rail transport could not take place.

Table 1   Basic requirements of rail transport operators

	Managing authority	*Railway operators*	*Railway freight operators*	*Transport order parties*	*Regions*
Safety	X	X	X	X	X
Logic system	X	X	X	X	X
Smoothness	X	X	X	X	
Transport service	X		X	X	X
Modernisation		X	X	X	
Profit		X	X		
Competitiveness	X				X

The final group of process factors affecting the functionality of rail transport systems are systemic threats and the impacts arising from disruption of the system. Systemic threats can be classified from different perspectives – internal and external threats, anthropogenic and naturogenic threats, deliberate and unintentional threats, etc. It is also possible to assess the risk factor of rail transport from the information concerning accidents in this sector (Maalel et al., 2014). In the context of these threats, it is necessary to define all risks, especially for the following areas of the railway system: transport processes, transport system, rail transport management, transport infrastructure and railway guided vehicles (Dvorak et al., 2010). The system is also heavily impacted by disruption to critical elements (e.g., Luskova et al., 2015). These disruptions may subsequently affect railway transport operators (e.g., financial loss, time delays for the order party, etc.), transport processes (e.g., delays or complications in organising rail transport), related infrastructure (e.g., violation of the functionality of dependent elements) or the functionality of links (e.g., supply restrictions, need for substitute resources).

Defining the key technical and process factors that determine and influence criticality assessments forms the methodological basis for assessing the criticality of railway infrastructure elements. From this methodological basis, a tool for integral assessment of the criticality of these elements can be created.

3   Railway infrastructure criticality assessment – RICA tool

The RICA tool was developed primarily for the needs of the most important rail operator in the Czech Republic (i.e., the Czech Railway Infrastructure Administration) and its security staff in individual regional directorates. It meets the primary requirements of this operator in regard to comprehensiveness, clarity, ease of applicability (Slivkova et al., 2018) and its assessment capabilities (primarily based on available data). Other entities, however, such as rail transport operators and freight forwarders, can also use this tool in the Czech Republic or abroad.

The RICA Tool assesses elements from the bottom-up. First, LEs (individual tracks) are assessed as the basic components of the railway, followed by PEs as a complement to LEs and finally AEs as special sites along the railway line. Assessing the elements is performed macroscopically: for the purposes of assessment, elements are simplified and made into integrated components.

The input necessary for correct application of the criticality assessment process using the RICA Tool were developed within the framework of the railway infrastructure elements assessment system (Slivkova et al., 2018). The framework integrates individual elements of railway infrastructure, rail transport stakeholders, transport process requirements, legal requirements, technical standards and internal guidelines as well as basic methodology.

3.1 The criticality assessment process

The RICA Tool is a critical assessment process whose output is the basis for identifying critical railway infrastructure elements and their subsequent protection (Figure 2). This process consists of three ordered sub-processes to provide continuity in evaluation.

Figure 2 Sub-processes of the critical infrastructure criteria assessment process
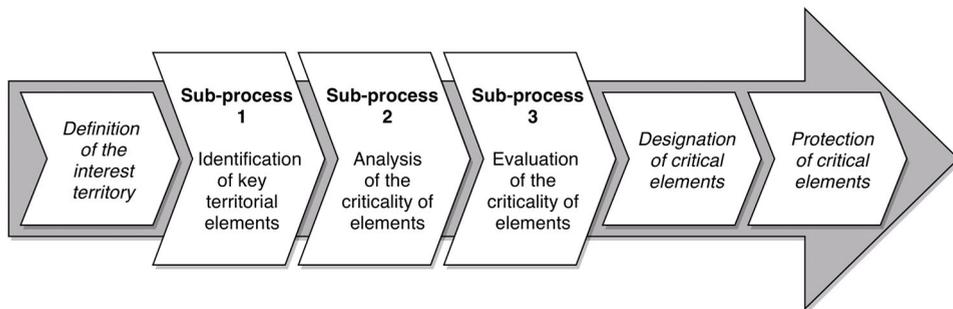
Sub-process 1: identification of key territorial elements

In any defined area it is necessary to identify all the key infrastructure elements, such as transport management elements (e.g., transport control systems), safety elements (e.g., signals) and elements difficult to replace (e.g., tunnels, bridges). These elements are then classified according to three groups: line, point and AEs (Rehak et al., 2019; Fekete, 2018).

Sub-process 2: analysis of the criticality of elements

Analysis of the criticality of railway infrastructure elements in a defined area takes place in three ordered stages:

1   analysis of the criticality of LEs

2   analysis of the criticality of PEs

3   analysis of the criticality of AEs.

The criticality assessment criteria are defined for each stage, for which detailed descriptions are presented below. Each key element identified within a given group must be assessed in the given stage.

The critical analysis consists of five steps:

1   data collection for the requirements of individual criteria

2   determination of simple criticality (i.e., transformation of the data obtained into a uniform assessment scale according to each criteria)

3   preferential consideration of the significance of the given criteria using weighted coefficients

4   determination of the weighted criticality of elements

5   determination of the resultant criticality of elements.

The weighted coefficients are determined according to the expert assessment of the rail operator (i.e., the Czech Railway Infrastructure Administration) using the pairwise comparison method. The resultant normalised weight values are presented as a part of the presentation of individual criteria for line, point and AEs. By its very nature, the expert assessment and its derived scales will always be somewhat subjective. However, given that intense research is still ongoing in this area, no widely accepted hierarchy of items is available.

Weighted criticality is determined according to the equation (1):

$$WC_{iC} = SC_{iC} \cdot w_c \tag{1}$$

where WC_{iC} = weighted criticality of ith element for the Cth criterion [%], SC_{iC} = simple criticality of ith element for the Cth criterion [%] and w_C = the weighted coefficient of the Cth criterion.

The resultant criticality is determined according to the equation (2):

$$FC_i = \sum_{C=1}^{n} WC_{iC} \tag{2}$$

where FC_i = the final criticality of the ith element [%] and WC_{iC} = the weighted criticality of the ith element for the Cth criterion [%].

Sub-process 3: evaluation of the criticality of elements

Final evaluation of criticality is based on comparing the resultant values of the analysed elements to the defined reference criticality values. A clearly defined borderline level is a crucial step in correctly identifying critical elements (Luiijf et al., 2003; Celko and Dvorak, 2018). The borderline level of criticality to determine critical elements is specified in four categories according to the scale of impact arising from disturbing or failure of the function of the element under evaluation. These values are set out and explained in the following sections.

3.2   Criteria for assessing elements of criticality

An important part of the process in identifying critical elements is defining and correctly establishing the assessment criteria, primarily according to the rail operator's

requirements. These criteria are created for each set of elements, i.e., LEs, point elements (PE), and AEs. Their different significance is considered using weighted coefficients. Because of the different units of expression in the natural values of the criteria, these values are converted into a uniform rating scale, which is expressed as a percentage (so-called simple criticality value).

3.2.1 Criteria for analysing the criticality of LEs

The specific criteria for assessing criticality in the first stage considers the significance of the railway (criterion L1 with a weight of 0.1), transport performance (criterion L2 with a weight of 0.4), the possibility of an alternative route (criterion L3 with a weight of 0.3) and track risks (criterion L4 with a weight of 0.2).

The significance of the track (L1) is primarily based on the category of railway to which the LE belongs. Railway categories are defined according to the Common Safety Methods (Agency for Railways, 2016) as:

- international corridors and national railways (100% simple criticality)

- regional railways (90% simple criticality)

- sidings (50% simple criticality)

- local, testing and special tracks (0% simple criticality).

From the point of view of the railway operator, the national and regional railways are of the utmost importance and primarily provide transport services to the state and region. However, when assessing simple criticality, the fact that national railways are also of international importance must be considered. For these reasons, national railways are rated at a simple criticality of 100% and regional rail at 90%. Sidings are only relevant to the rail operator to meet the needs of the national economy (sidings connect some companies to regional and national railways). According to these factors, sidings are assigned a simple criticality of 50%. Local railways, testing and special tracks have zero significance to the Czech Railway Infrastructure Administration.

The second criterion for assessing the criticality of a LE is transport performance on a monitored track (L2). Performance under this criterion is assessed by the number of freight and passenger transports on a given rail path per unit of time, which is known as the 24-hour carrying capacity of the track. The values of simple criticality of this criterion are reflected in the performance of the most efficient track of the regional headquarters, which is rated 100%. Compared to the performance of the most efficient track, the simple criticality of other rated tracks can be determined as a ratio of their performance (e.g., half performance will be rated at 50%).

Another criterion is the possibility of replacing the failure of the observed element (L3), that is, the possibility of an alternative route. From the point of view of the rail operator, the use of an alternative route is primarily assessed in this criterion. The values of the simple criticalities therefore correspond to these conditions:

- the monitored track has an alternative route that corresponds to the parameters of the section requiring by-pass – simple criticality = 0%

- the monitored track does not have an alternative route (i.e., carriers must use alternative road transport in the event of track failure) – simple criticality = 100%.

An important step in analysing the criticality of LEs is a risk assessment of the given track and related equipment (L4). A risk assessment of the track primarily corresponds to the sections monitored by the Czech Railway Infrastructure Administration that have a frequent occurrence of major emergencies. Specific risks include:

- damage to tracks because of floods

- damage to tracks because of special floods

- emergency because of snow on tracks

- landslides on tracks

- fallen trees on tracks

- leakage of hazardous substances on the track circuit

- damage to tracks because of heat.

Risk rates for each of the above-defined events must be expressed for the monitored track. For this purpose, the failure mode, effects and criticality analysis method (IEC, 2006) can be applied. The resulting value of the simple criticality of the element in this criterion is represented by the percentage expression of the sum of all risks applicable to the element up to the maximum possible sum of the risk levels.

3.2.2   Criteria for analysing criticality of point elements

The specific criteria for assessing criticality in the second stage takes into account the criticality of LEs (criterion P1 with a weighted preference of 0.1), the influence and dependence of the element (criterion P2 with a weighted preference of 0.4), the substitutability of the element (criterion P3 with a weighted preference of 0.3), and the risks for the element (criterion P4 with a weighted preference of 0.2).

The first criterion in evaluating a point element is the criticality of the LE (P1). This criterion reflects the fact that increasing the criticality of a LE increases the level of criticality of the point element. In this criterion, the value of the resultant LE criticality where the observed element fulfils its function is transferred to the point element assessment (the value of the resultant criticality of the LE corresponds to the value of the simple criticality of the point element for this criterion).

The criterion of the influence and dependence of element (P2) takes into account all the elements that are dependent on the observed point element (so-called dependent elements) and all the elements that could, by contrast, influence the observed element (the so-called influential elements). An assessment of the simple criticality of a given element is then performed according to Table 2.

The substitutability criterion (P3) considers the possibility of replacing the observed element with another element without any significant loss of system function, or the possibility of providing a substitute element. The values of the simple criticalities of individual point element types correspond to the option of replacing an observed element with another element, or with a substitute solution that fulfils the missing feature of an element. An element that cannot be replaced in any way is rated at a simple criticality of 100%. Conversely, an easily replaceable element acquires a simple criticality of 0%. The specific values of the simple criticalities of substitutability from the track operator's point of view for individual point element types are defined in Table 3.

Table 2 Matrix for assessing the simple criticality of P2 criteria

	6	70%	80%	90%	100%
	5	60%	70%	80%	90%
	4	50%	60%	70%	80%
Number of dependent elements	3	40%	50%	60%	70%
	2	30%	40%	50%	60%
	1	20%	30%	40%	50%
	0	10%	20%	30%	40%
		1	2	3	4
		Number of influential elements			

Table 3 Values of the simple criticalities for the P3 substitutability criterion

Point elements	Values of simple criticalities
Traffic control workplaces	100%
Track constructions	100%
Electrical equipment	100%
Electro-dispatching workplaces	100%
Station signals	90%
Track signals	90%
Telecommunications equipment	90%
Operating control posts without station signals	80%
Railway crossing signals	50%
Switching systems	50%
Halts	20%
Railway crossings without crossing signals	10%

Finally, each point element is subjected to the element risk criterion (P4). This criterion follows the LEs criticality analysis criterion L4 – Track risks. In this identification process, risks that have already been assessed in relation to the line track on which the monitored element fulfils its function can be omitted. Specifically, the following risks are involved:

- damage to equipment because of a fire on the track circuit
- damage to equipment because of material defects
- damage to equipment caused by traffic accidents
- damage to equipment caused by incorrect train movements
- emergency caused by failure in control technology
- theft of or sabotage to track equipment.

Assessing the element's simple criticality rating in this criterion is based on the same approach as in LE criticality L4 – track risks, with different possible events.

3.2.3   Criteria for analysing the criticality of AEs

The specific criteria for assessing criticality in the third stage takes into account the criticality of LEs (criterion A1 with a weighted preference of 0.3), the criticality of point elements (criterion A2 with a weighted preference of 0.4), the complexity of elements (criterion A3 with a weighted preference of 0.1) and the option of alternative routes (criterion A4 with a weighted preference of 0.2).

The first criterion for assessing the criticality of LEs is A1. Each LE relates to at least one linear element whose increasing criticality increases the criticality of the AE.

When a LE is a single LE, the value of the simple criticality of this criterion is the value of the resultant criticality of the LE. If the LE consists of several LEs, the value of the criticality of this criterion is the value of the resultant criticality of the LE that has the highest final criticality (the criticality value of the most critical LE corresponds to the criticality value of the AE for this criterion).

The criticality of point elements (A2) takes into account all the point elements that make up the assessed AE. The criticality of point elements expresses the criticality of at least two point elements. The value of the simple criticality of this criterion is the weighted average of the resultant criticality values of all point elements that fulfil the function in the given AE. The weights are determined by the number of dependent elements in relation to the element under observation.

The complexity of the AE (A3) reflects the fact that increasing complexity can increase the criticality of a given element. The assessment corresponds to the simple criticality values derived in consultation with the track operator:

- if the element consists of no more than 5 point and LEs = 20%

- if the element consists of 6 point and LEs = 40%

- if the element consists of 7 point and LEs = 60%

- if the element consists of 8 point and LEs = 80%

- if the element consists of 9 point and LEs = 100%.

The criterion of the alternative route option (A4) follows the L3 criterion, which is the option of an alternative route based on the LEs analysis. However, in this case, it is the strategic placement of the AE in the rail system of a given region or territory that is assessed. From the point of view of the track operator, this criterion primarily evaluates the possibility of an alternative route in AE. The simple criticality values therefore correspond to the following conditions:

- the observed AE has an alternative route matching the parameters of the by-passed section – simple criticality = 0%

- the observed AE does not have an alternative route (i.e., carriers must use road transport in the event of a failure) – simple criticality = 100%.

3.3   Referential values of criticality

In the final stage of assessing the criticality of railway infrastructure elements, the derived criticality element values must be compared to the reference values (Table 4),

which then allows elements to be classified according to four categories. The first two categories include elements that are still considered key elements, since their disruption or malfunction would only result in disruption to the flow of traffic. The other two categories include critical elements whose disruption or malfunction would result in halting traffic.

Table 4 Reference values for assessing the criticality of railway infrastructure elements

Interval	Category	Impact
(81;100)	Critical elements of category 1	Disturbance or failure of the function of elements in this category would result in halting traffic in several regions.
(62;81)	Critical elements of category 2	Disruption or failure of the function of elements in this category would result in halting traffic in the region concerned.
(43;62)	Key elements of category 1	Disturbance or failure of the function of elements in this category would result in disruption to the flow of regional traffic.
(0;43)	Key elements of category 2	Disturbance or failure of the function of elements in this category would result in disturbing the flow of local traffic.

The breakdown of criticality levels and establishment of reference values given in Table 4 is based philosophically on the Failure Mode, Effects and Criticality Analysis (IEC, 2006), which uses multiple variables to determine risk level and is based on the extreme values of variations in an assessment of their statuses. Similarly, different levels of criticality have been established that take into account extreme values (i.e., 1 and 4) in the cases of four criteria:

- $1,1,1,4 => \varnothing\ 1.75 => 43.7\%$

- $1,1,4,4 => \varnothing\ 2.50 => 62.5\%$

- $1,4,4,4 => \varnothing\ 3.25 => 81.2\ \%$

- $4,4,4,4 => \varnothing\ 4.00 => 100\%$

First, attention should be given to the critical elements of I and II whose disruption or malfunction would result in halting traffic. Specifically, it should involve defining and implementing adequate safety measures to ensure the preparedness or enhanced resilience of designated elements (e.g., Rehak et al., 2018; Stoller et al., 2018; Klein and Hutter, 2017; Hromada and Lukas, 2012; Dvorak et al., 2013).

4   Example of a practical RICA tool application

For a practical demonstration of the proposed railway infrastructure criticality assessment (RICA tool), a case study was prepared. This study focused on the assessment of critical elements in the section between Břeclav and Podivín, located in south-eastern Czech Republic. The underlying data was provided by the rail operator, i.e., the Czech Railway and Transport Administration.

The area of interest is the line section between the towns of Břeclav and Podivín (Figure 3). The section is on line number 250 and is 11 km long. The owner of this line is the Czech Railway Infrastructure Administration.

Figure 3   The assessed line section between Břeclav and Podivín (see online version for colours)
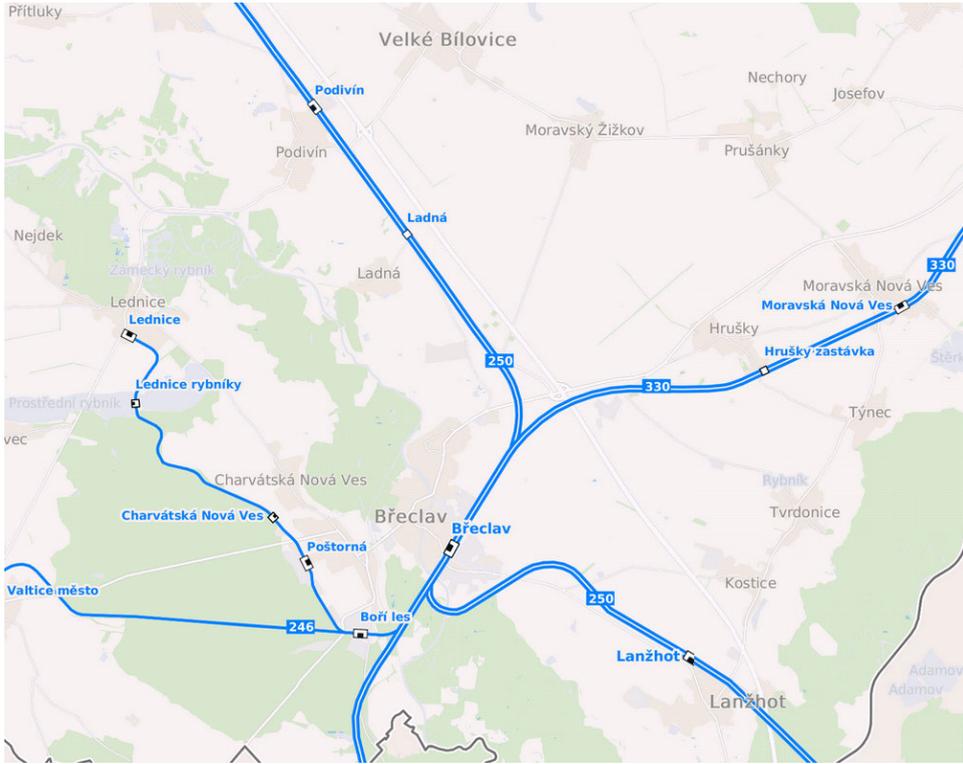
Source: Czech Railways (2018)

Sub-process 1: Identification of key elements

The following key elements were identified at the designated line section:

1   Line elements:
   - Břeclav – Podivín intermediate section (LE1)

2   Point elements:
   - Břeclav station signals (PE1)
   - Břeclav station territory track signals (PE2)
   - Břeclav station traffic control workplace (PE3)
   - Břeclav station switching systems elements (PE4)
   - Břeclav station telecommunications elements (PE5)

- Břeclav station electrical equipment elements (PE6)
- Ladná halt (PE7)
- Podivín station signals (PE8)
- Podivín station territory track signals (PE9)
- Podivín station switching system elements (PE10)
- Podivín station telecommunications elements (PE11)
- Podivín station electrical equipment elements (PE12)
- Level crossing at Podivín station (PE13)
- Railway crossing signals at Podivín station crossing (PE14).

3 Areal elements:

- Břeclav railway station (AE1)
- Podivín railway station (AE2)
- Crossing at Podivín station (AE3).

Sub-process 2: Elements criticality analysis

The criticality analysis of railway infrastructure on this section of track consisted of three stages: (Stage I) LEs criticality analysis; (Stage II) Point elements criticality analysis; and (Stage III) AEs criticality analysis.

Stage I: LEs criticality analysis

First, the identified LE1 line element was analysed. The underlying data were evaluated according to the relevant criteria for assessing line elements (L1–L4). The weighted criticality of the given element was determined according to equations (1) and (2). The results are presented in Table 5.

Table 5   Critical analysis of LEs on the Břeclav–Podivín track section

Criterion	L1 Track significance	L2 Transport performance	L3 Alternative route option	L4 Risks of the track	Σ
Criteria weight	0.1	0.4	0.3	0.2	
Simple criticality	100	80	0	28.6	
Weighted criticality	10	32	0	5.7	47.7

The assessed track section achieves 47.71% criticality.

Stage II: Point elements criticality analysis

In the next stage, the identified point elements PE1–PE14 were analysed. The underlying data were evaluated according to the relevant criteria for assessing point elements (P1–P4). The weighted criticality values for individual point elements were determined according to equations (1) and (2) and are presented in Table 6.

Table 6   Criticality analysis of point elements on the Břeclav-Podivín track section

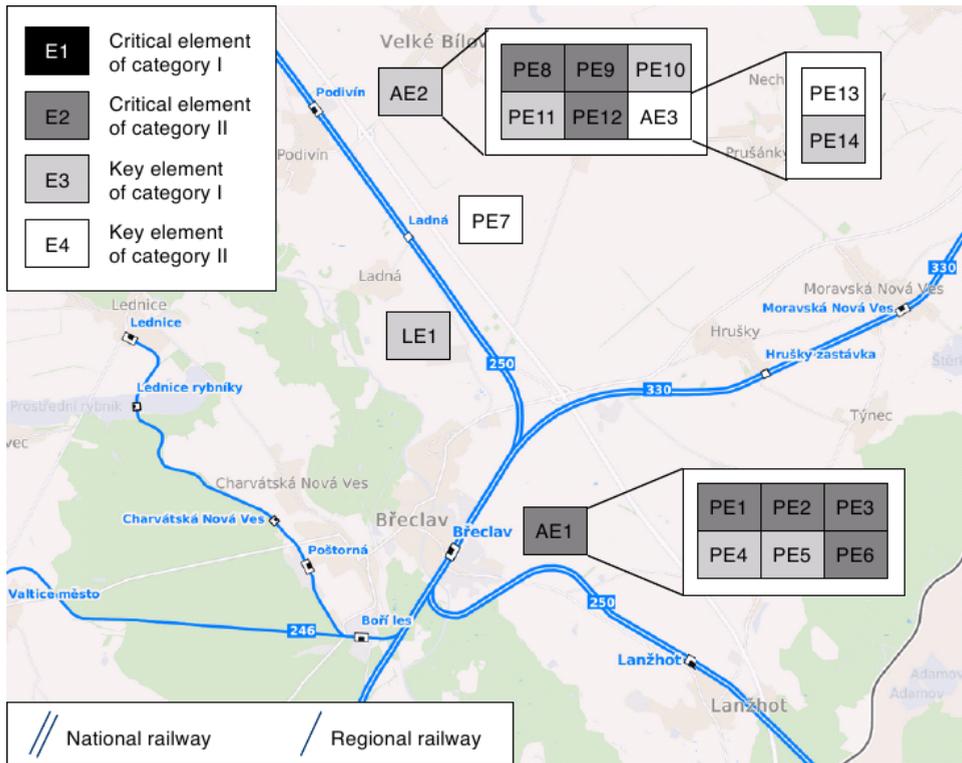| Element	Simple criticality				Weighted criticality
	P1: Line elements criticality	*P2: Element influence and dependence*	*P3: Element substitutability*	*P4: Element risks*	
Criteria weight	*0.1*	*0.4*	*0.3*	*0.2*	
PE1	47.7	50	90	72.2	66.2
PE2	47.7	50	90	77.8	67.3
PE3	47.7	60	100	66.7	72.1
PE4	47.7	30	50	61.1	44.0
PE5	47.7	40	90	50.0	57.8
PE6	47.7	70	100	66.7	76.1
PE7	47.7	20	20	50.0	28.8
PE8	47.7	50	90	72.2	66.2
PE9	47.7	50	90	77.8	67.3
PE10	47.7	30	50	61.1	44.0
PE11	47.7	40	90	50.0	57.8
PE12	47.7	70	100	66.7	76.1
PE13	47.7	20	10	38.9	23.5
PE14	47.7	50	50	55.6	50.9

Stage III: AEs criticality analysis

In the final stage, the identified areal elements AE1–AE3 were analysed. The underlying data were evaluated according to the relevant criteria for assessing areal elements (A1–A4). The weighted criticality values for individual AEs were determined according to equations (1) and (2) and are presented in Table 7.

Table 7   Critical analysis of AEs on the Břeclav-Podivín track section

Element	Simple criticality				Weighted criticality
	A1: Line elements criticality	*A2: Point elements criticality*	*A3: Element complexity*	*A4: Alternative route option*	
Criteria weight	*0.3*	*0.4*	*0.1*	*0.2*	
AE1	47.7	69.7	100	100	72.2
AE2	47.7	63.8	80	0	47.8
AE3	47.7	37.2	20	0	31.2

Figure 4   Assessed element categories on the track section between Břeclav and Podivín
            (see online version for colours)

Sub-process 3: Elements criticality assessment

In the final sub-process, the resultant values of the weighted criticalities of the individual elements are compared to the boundary levels of criticality (Table 4) and classified according to the following four categories:

1   Critical elements of category I (81;100):

  - no element has been included in this category.

2   Critical elements of category II (62;81):

  - Břeclav station signals (PE1)

  - Břeclav station territory track signals (PE2)

  - Břeclav station traffic control workplace (PE3)

  - Břeclav station electrical equipment elements (PE6)

  - Podivín station signals (PE8)

- Podivín station territory track signals (PE9)
- Podivín station electrical equipment elements (PE12)
- Břeclav railway station (AE1).

3   Key elements of category I (43;62):
- Břeclav – Podivín intermediate section (LE1)
- Břeclav station switching system elements (PE4)
- Břeclav station telecommunications elements (PE5)
- Podivín station switching system elements (PE10)
- Podivín station telecommunications elements (PE11)
- Railway crossing signals at Podivín station crossing (PE14)
- Podivín railway station (AE2).

4   Key elements of category II (0;43):
- Ladná halt (PE7)
- Level crossing at Podivín station (PE13)
- Crossing at Podivín station (AE3).

From the results of the case study, the following were clearly identified on the assessed section of track: eight critical elements of category 2, seven key elements of category 1 and three key elements of category 2. A graphical representation of the assessment results is presented in Figure 4.

5   Discussion

In the previous sections of the article, key factors determining and influencing criticality were identified. These factors were subsequently taken into account in the proposed RICA tool, which allows an integrated assessment of the criticality of railway infrastructure elements. An example of the practical application of the proposed tool was subsequently presented as a case study. The aim of this part of the article is to discuss the benefit and added value of the proposed RICA tool compared to existing tools and methods.

To this end, five tools and methods were selected to assess the criticality of rail infrastructure, which are by their approach closest to the proposed RICA tool:

- method for identifying and ranking critical components and sets of components in technical infrastructures (Jönsson et al., 2008)
- infrastructure interdependencies simulator (i2Sim) (Alsubaie et al., 2015)
- framework for assessing the vulnerability of rail freight networks by introducing two bi-level models (Bababeik et al., 2017)
- procedure for identifying potential CI elements in the railway sub-sector (Leitner et al., 2017)
- methodology for identifying critical infrastructure objects in transport (Dvorak et al., 2017).

Table 8 Comparative analysis of the usability of selected instruments and methods for integral critical evaluation of railway infrastructure elements

Selected tools and methods	Evaluation process methodology	Identification of potential critical elements	Level of evaluation	Evaluation of elements of different topology	Integrated evaluation areas	Need for supporting software
Railway infrastructure criticality assessment tool (RICA tool)	Understandable, easy to implement, semi-quantitative, integral evaluation	Facilitates	Elementary (elements of railway infrastructure)	Point, areal, line	Interdependence, substitutability, risks, consequences of failure, significance, performance	Not needed, simple spreadsheet tools can be used for simplification
Method for identifying and ranking critical components and sets of components in technical infrastructures	Understandable, difficult to implement, quantitative, integral evaluation	Facilitates	Network	Areal, line	Consequences of failure, vulnerability	At least a simple (optimally special) tool is needed
Infrastructure interdependencies simulator (i2Sim)	Difficult to understand, difficult to implement, quantitative, integral evaluation	Facilitates	Network	Areal, line	Interdependence, consequences of failure, vulnerability	A special evaluation tool (simulator) is needed
Framework for assessing the vulnerability of rail freight networks by introducing two bi-level models	Difficult to understand, difficult to implement, quantitative, integral evaluation	Facilitates	Network	Line	Vulnerability, economic aspect, time aspect, operating data, consequences of failure	A special evaluation tool (simulator) is needed (programming models)
Procedure for identifying potential CI elements in the railway sub-sector	Understandable, easy to implement, semi-quantitative, separate evaluation	Does not facilitate	Elementary (elements of railway infrastructure)	Point, areal, line	Significance, performance, vulnerability, design data	Not needed, simple spreadsheet tools can be used for simplification
Methodology for identifying critical infrastructure objects in transport	Understandable, easy to implement, qualitative, separate evaluation	Facilitates	Elementary (elements of transport infrastructure)	Point, areal, line	Risks, vulnerability, design data, economic aspect, renewability	Not needed, simple spreadsheet tools can be used for simplification

The above tools and methods were compared using a set of criteria reflecting defined evaluation conditions, i.e., by taking into account the key factors determining and influencing the criticality assessment of all elements of the railway infrastructure. For this purpose, the following comparative criteria were set:

- evaluation process methodology

- identification of potential critical elements

- level of evaluation

- evaluation of elements of different topology

- integrated evaluation areas

- need for supporting software.

On the basis of these criteria, a comparative analysis of the selected tools and methods was performed. Attention was given to the accessibility, complexity and practical application of these tools and methods. The results of the comparative analysis are presented in Table 8.

From the results of the comparative analysis it is clear that the presented methods differ from each other especially in terms of their demandingness, specificity and complexity of application. Although all methods deal with evaluating critical elements in railway infrastructure, the individual approaches are so different that they cannot be effectively compared to each other. For example, methods that allow integral evaluation (i.e., Jönsson et al., 2008; Alsubaie et al., 2015; Bababeik et al., 2017) only access evaluation in a networked manner and require the use of specific software tools, whereas methods allowing elementary evaluation (i.e., comprehensive evaluation of point, areal and LEs) only approach evaluation in a separate manner and thus do not take into account all factors (i.e., Leitner et al., 2017; Dvorak et al., 2017).

Based on this observation, it can be stated that the proposed RICA Tool successfully fills a research gap in the methodology for evaluating the criticality of railway infrastructure elements. The method is comprehensible, easy to implement, and allows integral assessment at an elementary level.

6   Conclusions

Assessing critical elements to subsequently identify and protect them is now an integral part of the railway transport safety process. A cyclical application not only ensures the continuous assessment of critical elements but also highlights security measures already implemented or new risks.

The RICA tool uses an integral approach consisting of a comprehensive assessment of the technical and process factors in rail transport. The criticality of railway infrastructure elements is thus assessed not only in terms of the relevance and resilience of those elements but also their interdependence, substitutability, risk and impact. This tool permits criticality to be comprehensively assessed and provides continuous correlation between the assessed elements of various topological structures, i.e., line, point and AEs.

The RICA Tool is specific in that it allows a sequential assessment of criticality. The essence of this assessment method is to take into account the functional links between individual groups of elements. Analysis of criticality in railway infrastructure elements is thus performed in three stages, each being conditional on the previous stage. Stage I assesses LEs forming the basic level of infrastructure. In stage II, point elements that support and whose function is bound to LEs are then evaluated. To factor in the link between line and point elements, the results of the previous assessment stage are always reflected in the following stage. Similarly, links are considered in the function of AEs. Sequential assessment therefore allows assessment to be completed at the end of any stage, but must always be performed beginning with LEs, then point elements and finally AEs.

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