VULNERABILITY ASSESSMENT OF TRANSPORT INFRASTRUCTURE ELEMENTS - CASE STUDY IN RAJEC

Jozef Kubás[1,*], Boris Kollár[1], Jozef Ristvej[1], Katarina Petrlová[2], Kateřina Blažková[3]

[1]Department of Crisis Management, Faculty of Security Engineering, University of Zilina, Zilina, Slovakia
[2]Mathematical Institute in Opava, Silesian University in Opava, Opava, Czech Republic
[3]Fire Rescue Brigade of Moravian-Silesian Region, Ostrava - Zabreh, Czech Republic

*E-mail of corresponding author: jozef.kubas@uniza.sk

Jozef Kubas 0000-0002-0512-6505, Boris Kollar 0009-0006-8588-5398, Jozef Ristvej 0000-0002-2290-1470

Resume

The risk assessment of the area, with emphasis on the transport infrastructure, is dealt with in this paper. Disruption of some elements of transport infrastructure can lead to major negative impacts on the functioning of society, economies or states. The article therefore starts with presentation of the characteristics and importance of the road transport infrastructure with regard to its vulnerability. The core of the paper is the identification of vulnerable elements of road transport infrastructure and their parts and the subsequent vulnerability assessment of the selected element of the road transport infrastructure in the selected area. Therefore, the aim of the research, presented in this paper, was to propose a method for identifying and assessing the vulnerability of road transport infrastructure elements using the latest approaches in the field of vulnerability assessment. The proposed vulnerability assessment procedure is applied in the conditions of the city of Rajec in Slovakia.

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1 Introduction

The introductory part of the paper is focused on the definition of the basic theoretical background, with an emphasis on critical infrastructure and risk assessment. At the outset, it is necessary to emphasize the understanding of the concepts of a critical infrastructure and significant infrastructure elements.

The critical infrastructure in the Slovak Republic is defined in Act No. 45/2011 Coll. on Critical Infrastructure. This definition is based on the currently repealed Council Directive 2008/114/EC of 8 December 2008, which is replaced by Directive 2022/2557 of the European Parliament and of the Council of the European Union of 14 December 2022 on the resilience of critical entities. The critical infrastructure consists of system elements that are classified into sectors. By elements it is meant, in particular, engineering structures, services and information systems in the critical infrastructure sector that perform functions in the public interest and whose disruption or destruction, according to sectoral and cross-cutting criteria, would have a serious negative impact on the performance of the economic and social functions of the State. At the same time, the population, property and the environment would be endangered [1].

Significant infrastructure elements are those elements whose disruption or destruction would have major consequences for the selected territory in which they are located, but which do not meet the criteria for inclusion in a national or European critical infrastructure.

Examples of such an approach include different methodologies for assessing the risks of an area. In these methodologies, significant infrastructure elements are treated differently. For example, these may be critical facilities or safety-critical objects, etc. [2-3]. This concept has also been addressed, for example, by Novotny et al. [4] or in the work of Kong et al. [5].

With respect to the road transport infrastructure, it is possible to identify engineering structures that have the potential to be classified as Critical Infrastructure Elements or Significant Road Infrastructure Elements. According to Act No. 50/1976 Coll. on spatial planning and building regulations, these include in particular, motorways, roads, local and special-purpose roads, bridges, overpasses, and tunnels [6].

In the Slovak Republic, the road transport is a separate sub-sector within the transport sector. The Ministry of Transport and Construction of the Slovak Republic oversees the transport sector [1]. The road transport is the most widespread type of transport in Slovakia. The importance of this type of transport lies in its ability to connect individual regions, districts, towns, and municipalities. The road transport is a crucial element for ensuring the international cooperation and trade, as well [7].

The importance of individual roads is also reflected in their classification. In the conditions of the Slovak Republic, this mainly involves the division into motorways, expressways and roads of the 1st, 2nd and 3rd classes. The road structures, such as bridges or tunnels, are built to ensure safe, smooth and economical traffic on the roads and to overcome various natural and man-made barriers [8].

The importance of the road infrastructure can also be highlighted regarding the protection of the population. The road infrastructure serves to supply the population with food and drinking water, even in the event of a crisis or extraordinary events. It is also used by the integrated rescue system for moving to the location of an extraordinary event.

The aforementioned roles of road infrastructure reflect its importance to society and the state. It is therefore necessary to protect individual elements of the critical road infrastructure and significant elements of road infrastructure. The importance of the road transport infrastructure elements can also be illustrated with examples from around the world. For instance, the collapse of the I-35W bridge in Minneapolis (USA) caused economic losses ranging from $77,000 to $220,000 per day [9]. Another example is the economic damage caused by landslides to road infrastructure in Scotland [10].

The protection of a critical infrastructure element involves ensuring its functionality, integrity and continuity of operation to prevent its disruption or destruction. Protection is ensured through mechanical barriers, technical safeguards, cybersecurity measures, physical protection, organizational measures, control measures or a combination of these [1].

The critical infrastructure protection is a process that considers all the risks and threats that could disrupt or destroy it. These risks, present in a particular area, may be natural or anthropogenic in nature, or may act in combination [11]. For protecting the road transport infrastructure elements, it is necessary to assess each risk, identify vulnerabilities and determine the possible consequences of its disruption or destruction [1]. By assessing all the road infrastructure elements in an area with respect to their vulnerability, it is also possible to determine the overall vulnerability of the area.

In the context of assessing both the vulnerability of the road transport infrastructure elements and the vulnerability of an area concerning these elements, it is necessary to define the concept of vulnerability. Hofreiter et al. (2013) defined the vulnerability as a characteristics of an object, technical facility or social entity that is expressed by a loss of ability to perform a natural or specified function. The loss of this capability is conditioned by the action of internal or external threats. Lovecek et al. further divided the vulnerability into three areas. These are physical vulnerability, technical vulnerability and operational vulnerability [12].

With respect to the impact of emergencies, it is also possible to characterize vulnerability in terms of a particular territory. In this case, vulnerability is expressed as a feature of the individual sub-elements of a particular territory. In general, vulnerability can be characterized as the susceptibility of a territory to the impacts of an extraordinary event, or the ability to react negatively to the consequences of crisis [13].

The vulnerability assessment of an object, territory or a society has recently received considerable attention. The vulnerability of the road transport infrastructure is not lagging behind in this respect. For example, the vulnerability assessment of the road infrastructure using territorial factors with the use of geographic information systems can be mentioned [14]. Another example is the road network vulnerability assessment model based on two factors considering seismic events [15].

Another interesting vulnerability assessment model from the transport sector is the railway key elements assessment model. The vulnerability assessment is based on main criteria that are identical for all the key elements and parameters set for each element separately. The advantage of the model is its simplicity, especially in terms of the data required for evaluation [16-17].

Considering the road infrastructure and its vulnerability, it is also necessary to identify the elements or parts of the infrastructure that are more susceptible or exposed to the effects of emergencies. For this purpose, a model for assessing the level of societal vulnerability, for example, can serve this purpose. This model uses indicators to determine the vulnerability of road and rail infrastructure [18].

Nowadays, the term resilience is also used to express the ability of the elements of a territory to cope with the impact of crisis phenomena. Resilience is the inverse of vulnerability. A higher level of resilience reduces vulnerability and vice versa [19]. Resilience can be characterized as the ability to absorb disruptive events, adapt to them, or quickly return to a desired state [20].

In the context of resilience and vulnerability, the notion of preparedness emerges. In crisis management issues, preparedness is one of the phases of the crisis management cycle. According to the authors in "Vulnerability and disaster preparedness", preparedness

Table 1 *Criteria for determining the susceptibility of road infrastructure elements to the effects of crisis events (processed by [18])*

Element type	Description of the risk
Element is located near the river	is at risk of being washed away, flooded or is directly in a flood risk area (flood maps).
Element is located below the slope	danger of rockslide, landslide, etc.
Element is located in a forest area	danger of falling trees and forest fires.
Element is located in a location threatened by strong wind	fall of trees, etc..
Element is located in mountainous areas	risk of avalanche or calamity.
Element is located in another area that has the potential to cause negative impacts	other risks based on actual condition

Table 2 *Detour route criterion and its parameters*

Detour route (K1)					
	Increase of the detour route by a percentage of the original one [%]				
	1-20	21-40	41-60	61-80	81-100
Length of detour route	Detour length				
	to 1.2x	1.21x-1.40x	1.41x-1.6x	1.61x-1.80x	1.81x-2x
Compliance with the vulnerability criterion [%]	20	40	60	80	100
Number of detour routes	0	1	2	3	4 and more
Compliance with the vulnerability criterion [%]	100	75	50	25	0
Full-value compensation	According to normal load capacity [%]				
	81-100	61-80	41-60	21-40	0-20
Compliance with the vulnerability criterion [%]	20	40	60	80	100

integrates the previous phases of the cycle. It includes established crisis plans, knowledge of the causes and the course of individual emergencies. It also includes the anticipation and recognition of impending hazards. Preparedness also means having ready organizational, personnel, management, technical, material and other measures in the case of a crisis event [21].

Preparedness is also a risk reduction measure [13]. Rehak et al. described resilience as the intrinsic readiness of subsystems for an adverse event [19]. Preparedness is often considered to some extent in vulnerability assessment in the context of risk assessment of territorial units [3, 13, 18, 22]. Thus, preparedness can be seen as a component of resilience that helps to increase it and at the same time reduce vulnerability.

The process of vulnerability assessment of the critical transport infrastructure elements and major road infrastructure elements is then itself a way of preparing for crisis events. The importance of assessing the vulnerability of the road transport infrastructure is based on the significance of these infrastructure elements and the need for planning and responding to emerging crisis phenomena. That is why the modification and use of vulnerability assessment models focused on transport infrastructure are discussed in the next part of the paper.

The choice of appropriate models is often influenced by the availability of data. Therefore, for the purposes of this paper, models that are relatively data-light have been selected. The proposed procedure in the following sections of the paper allows for assessing the vulnerability of the road transport infrastructure, which represents a significant part of the overall set of elements that determine the level of vulnerability of an area. At the same time, the selected and modified models are applied to the chosen territory.

2 Materials and methods

The authors focus in the article on the description and application of the selected models to a specific area, to identify and assess vulnerable parts of the road infrastructure elements. For this purpose, two vulnerability assessment models have been selected. Specifically, these are: Societal Vulnerability Level Assessment Model and the Model for the Assessment of the Key Railway Transport Elements [16-18].

The principles used in [17] were used to determine the criteria and evaluation parameters, which were adapted to the needs of the road transport infrastructure.

Table 3 *Criterion construction characteristics and their parameters*

Construction characteristics (K2)										
Bridge length to [m]:	102	203	304	405	506	607	708	809	910	1008
Compliance with the vulnerability criterion [%]	10	20	30	40	50	60	70	80	90	100

Construction characteristics (K2)			
Material of bridge	Material used		
	stone	steel	reinforced concrete
Compliance with the vulnerability criterion [%]	100	66	33

Construction characteristics (K2)					
Age of bridge	up to 25 years	26 - 52 years	53 - 77 years	78 - 103 years	104 years and over
Compliance with the vulnerability criterion [%]	20	40	60	80	100

Table 4 *Criterion element significance and parameters*

Significance of element (K3)			
Part of TEN-T	The bridge is located on a TEN-T road		
	Yes		No
Compliance with the vulnerability criterion [%]	100		0
Part of TEM	The bridge lies on a road that is part of the TEM		
	Yes		No
Compliance with the vulnerability criterion [%]	100		0
Part of the international road network „E“	The bridge lies on a road that is part of „E“		
	Yes		No
Compliance with the vulnerability criterion [%]	100		0
	Main category	Subcategory	Compliance with the criterion [%]
The economic significance of transport	Motorways and 1st class roads	Motorways and express roads	100
		1st class roads	80
	Other roads	2nd class roads	60
		3rd class roads	40
		Local roads	20

2.1 Identification of vulnerable elements

The Societal Vulnerability Assessment Model integrates the factors that determine a society's vulnerability. Those factors are categorized according to vulnerability drivers, which are mainly exposure and susceptibility factors. Within these factors, the indicators of the road network density (exposure), vulnerable parts of the road network (susceptibility) and vulnerability of road network objects are established [18].

The indicators under the exposure factor are based on the assumption that a higher density of the road network in an area represents a greater exposure to the effects of crisis events. The susceptibility indicators are used to select elements and parts of the road infrastructure that are more susceptible to crisis events. Criteria are developed within the model to identify these elements or parts of elements. Those criteria have been selected to identify the more susceptible (vulnerable) road infrastructure elements in the selected area [18]. These criteria are described in Table 1.

2.2 Vulnerability assessment of the road transport infrastructure

The vulnerability assessment of the identified vulnerable road infrastructure elements and their parts is based on the Model for the Assessment of the Key Railway Transport Elements [16-17]. As this model is primarily intended for the vulnerability assessment of

***Table 5** Criterion transport capacity and its parameters*

Transport capacity (K4)					
Traffic load [%]	Traffic load per population				
	to 50	to 90	to 100	to 150	over 150
Compliance with the vulnerability criterion [%]	20	40	60	80	100

***Table 6** Territory risk criterion and its parameters*

<table>
<tr><th colspan="8">Territory risk (K5)</th></tr>
<tr><td rowspan="4">Slope movements and deformations</td><td colspan="4">Characteristics of the area</td><td colspan="3">Compliance with the vulnerability criterion [%]</td></tr>
<tr><td colspan="4">High rate of occurrence of slope deformation</td><td colspan="3">100</td></tr>
<tr><td colspan="4">Mean rate of occurrence of slope deformations</td><td colspan="3">50</td></tr>
<tr><td colspan="4">Low rate of occurrence of slope deformations</td><td colspan="3">1</td></tr>
<tr><td rowspan="11">Floods</td><td colspan="4">Characteristics of the area</td><td colspan="3">Compliance with the vulnerability criterion [%]</td></tr>
<tr><td colspan="2" rowspan="3">Low probability</td><td colspan="2">Low range, low water level</td><td colspan="3">10</td></tr>
<tr><td colspan="2">Medium range, medium water level</td><td colspan="3">20</td></tr>
<tr><td colspan="2">Extensive flooding with high water levels</td><td colspan="3">30</td></tr>
<tr><td colspan="2" rowspan="3">Medium probability (>=100 years)</td><td colspan="2">Low range, low water level</td><td colspan="3">40</td></tr>
<tr><td colspan="2">Medium range, medium water level</td><td colspan="3">50</td></tr>
<tr><td colspan="2">Extensive flooding with high water levels</td><td colspan="3">60</td></tr>
<tr><td colspan="2" rowspan="3">High probability</td><td colspan="2">Low range, low water level</td><td colspan="3">70</td></tr>
<tr><td colspan="2">Medium range, medium water level</td><td colspan="3">80</td></tr>
<tr><td colspan="2">Extensive flooding with high water levels</td><td colspan="3">90</td></tr>
<tr><td colspan="4">Flood with disastrous consequences</td><td colspan="3">100</td></tr>
<tr><td rowspan="4">Torrential rains</td><td colspan="4">Course of the threat</td><td colspan="3">Compliance with the vulnerability criterion [%]</td></tr>
<tr><td colspan="4">Slight increase in level, not endangering the statics of the bridge</td><td colspan="3">1</td></tr>
<tr><td colspan="4">Bridge damaged by water overflow</td><td colspan="3">50</td></tr>
<tr><td colspan="4">Bridge destroyed by extremely high-water level</td><td colspan="3">100</td></tr>
<tr><td rowspan="2">Technical condition of the dilatation unit</td><td colspan="7">Condition of the dilatation unit</td></tr>
<tr><td>Perfect</td><td>Very good</td><td>Good</td><td>Satisfactory</td><td>Wrong</td><td>Very bad</td><td>Emergency</td></tr>
<tr><td>Compliance with the vulnerability criterion [%]</td><td>10</td><td>20</td><td>30</td><td>50</td><td>70</td><td>90</td><td>100</td></tr>
</table>

railway infrastructure elements, its adaptation to road infrastructure elements was necessary. The elements of railway infrastructure that are the focus of the model are the bridge, tunnel, broad gauge and marshalling yard [17]. For application of the model, the parameters of the main criteria for the bridge element were extracted from the model and modified.

The main assessment criteria and the modified parameters of these criteria, together with the scales for determining the vulnerability, based on the criteria, are included in Tables 2-6.

The parameters "Length of detour route" and "Number of detour routes" have remained unchanged, as they are also suitable for assessment of the road bridge. Parameter P3 will be assessed according to the normal load capacity of the bridges located on the detour route, taking into account the bridge with the lowest load capacity on the selected shortest detour route. If a bridge is not located on the detour route, the parameter will be assigned the lowest vulnerability value.

The "Bridge length" parameter for criterion K2 has been adjusted according to the length of road bridges.

Table 7 Scale for determining the vulnerability of the element under consideration (processed by [15])

Rating scale for bridge vulnerability				
Minimum	Low	Medium	High	Maximum
11.78	11.79-39.78	39.79-67.78	67.79-95.99	96

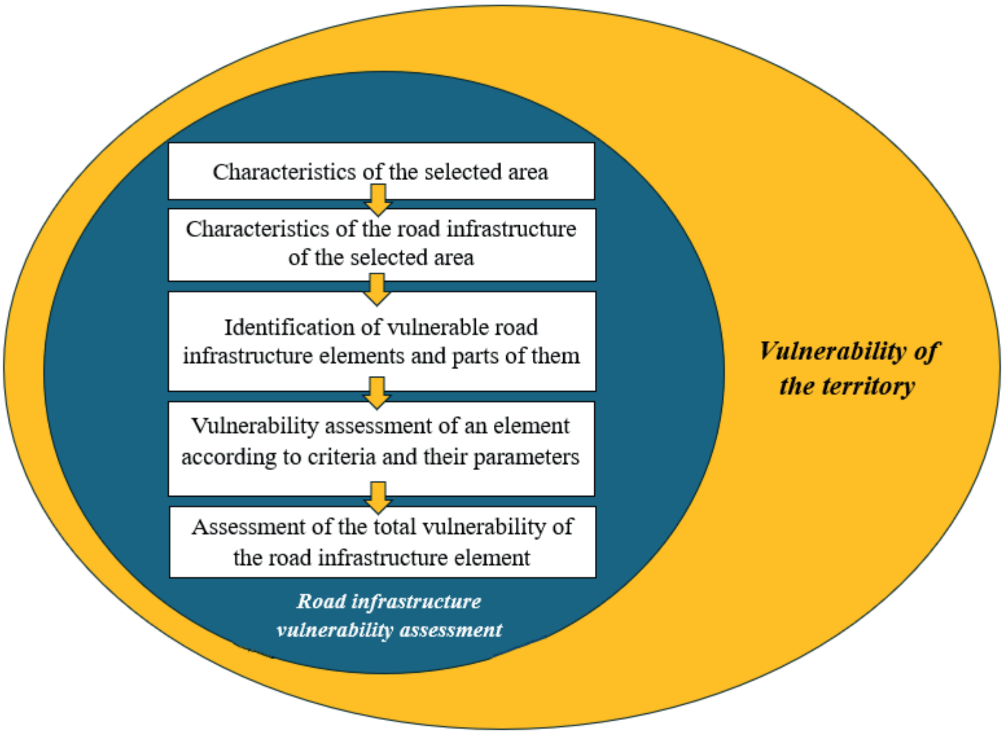

***Figure 1** Vulnerability assessment procedure for a road infrastructure element*

According to the technical data available on the website of the Slovak Road Administration, the longest road bridge M6437- Estakada nad zeleznicou in Zilina is 1007.76 metres long [23]. The Sturges' rule principle was used to create the intervals. Parameter P4 from the baseline model was not included in evaluation.

The parameters of the element importance criterion (K3) have been adjusted for the needs of road transport infrastructure in the Slovak Republic.

For this criterion, the original model parameter had to be replaced as it was not suitable for the road transport needs. The traffic load parameter is based on the traffic load data. The traffic load parameter is calculated as the ratio of the average number of motor vehicles that pass through the section closest to the bridge structure to the population living in the given municipality or city.

For the purpose of assessing the road bridge structures, it was necessary to modify the last parameter. For this purpose, a scale for evaluation of the expansion joints of bridge structures was used [24].

Criteria-based vulnerability according to these parameters is calculated through the following relation [17]:

$$Ki = \frac{\sum P_i}{number\ of\ parameters}, \tag{1}$$

where:
Ki is one of the criteria,
P_i is the value of the parameters of the criterion.

The total vulnerability of the road infrastructure element under consideration shall be calculated according to Equation (2) [17]:

$$Ve = \frac{\sum K_i}{5}, \tag{2}$$

where:
Ve is the total vulnerability of the element under consideration
Ki are the evaluation criteria.

For the purpose of assessing the vulnerability of the element under consideration, the authors of the model prepared a vulnerability scale. This scale is included in Table 7.

The vulnerability evaluation process for the selected road infrastructure element consists of five steps and is illustrated in Figure 1. In the context of a site-specific vulnerability assessment, this is constitute of the overall vulnerability. The overall vulnerability can only be fully assessed after evaluating the other elements of the territory, including various types of infrastructure, services, society and the natural conditions of the territory.

The preliminary assessment procedure, developed based on two established models and modified for the needs of the road transport infrastructure, is suitable for determining the vulnerability of individual elements. The advantage of this procedure lies in the relatively low complexity of obtaining the necessary data, combined with the application of criteria and parameters that characterize the individual elements of road transport infrastructure in a detailed manner. This can be advantageous compared to other models that require more extensive data collection and processing for assessment.

In the following section, the modified model for assessing the road infrastructure vulnerability is applied to the cadastral territory of the town of Rajec.

3 Implementation of the models in the selected territory

To identify potentially significant elements of the road infrastructure in the territory of Rajec, the criteria for determining susceptibility (sensitivity) from the model presented in Section 2.1 were used. For the vulnerability assessment of the selected transport infrastructure element, the modified model presented in Section 2.2, was used.

3.1 Characteristics of the selected area

The characteristics of the selected area are based on the document "Analysis of the area in terms of the occurrence of possible emergencies", processed at all levels of government under Act No. 42/1994 Coll. on Civil Protection of the Population. Territory characteristics consist of geographical, demographic and economic aspect specific to the area [25-26].

According to the administrative division of the Slovak Republic, the town of Rajec is located in the Zilina self-governing region within the Zilina district. The total area of Rajec's cadastral territory is 31.46 km², comprising 11.19 km² of agricultural land, 17.45 km² of forest land, and 2.82 km² of other non-agricultural land. The town lies in the Rajecka basin, a subdivision of the Zilina basin, and is part of the Vah River basin hydrologically. The Rajcianka River flows through the town, draining the entire area of interest with its right and left side tributaries. The left-hand tributary Ciernanka and the right-hand Porubsky brook contribute to the river's flow. The region's rainfall runoff is influenced by soil types, and precipitation levels typically exceed evaporation over the year. Stream flow follows a mid-mountain snow-rain regime, with peak levels occurring from March to May [27].

According to the Statistical Office of the Slovak Republic, the population of Rajec in 2022 was 5,818, which represents 3.61% of the Zilina district's total population. The town's population comprises 2,907 males (49.97%) and 2,911 females (50.03%) [28].

Rajec serves as an economic centre for surrounding municipalities, specializing in manufacturing agricultural machinery parts and carpets, alongside electrical and woodworking industries [29]. It holds regional significance and serves as the hub for the recreational Rajecka kotlina area. Rajec possesses substantial regional resources and spatial potential for creating employment opportunities in the secondary and tertiary sectors [27].

3.2 Characteristics of the road infrastructure in Rajec

The town of Rajec is connected to the main routes leading through the Slovak Republic via the I class road I/64 on the section Prievidza-Zilina. Rajec is also connected to Povazska Bystrica via the II class road II/517. Class I road I/64 is of supra-regional importance. The first-class road I/64 and the second-class road

Table 8 *Traffic characteristics of class I and II roads in Rajec (processed by [30])*

Section	Route	Trucks and buses	Passenger vehicles	Motorcycles	Total
91381	I/64	1384	8282	87	9753
91391	I/64	1123	5886	116	7125
91392	I/64	1031	5765	53	6849
92409	II/517	427	2111	25	2563

Table 9 *Significant elements of the road transport infrastructure of Rajec (processed by [23, 27, 31])*

Road transport infrastructure element	Length in the study area
Route I/64	3.21 km
Route II/517	3.72 km
Bridge M995 (I/64)	17.45 m
Bridge M5745 (II/517)	9 m
Bridge M3698 (II/517)	4.05 m

Table 10 *Technical characteristics of the M995 bridge (processed by [23])*

Characteristics	Description
Bridging	Rajcianka watercourse
Year of building	1963
Length of bridging	17.45 m
Type of construction	Beam
Material	Precast prestressed concrete
Normal load ability	16 t
Exclusive load ability	48 t
Exceptional load ability	88 t
Building-technical condition	Poor

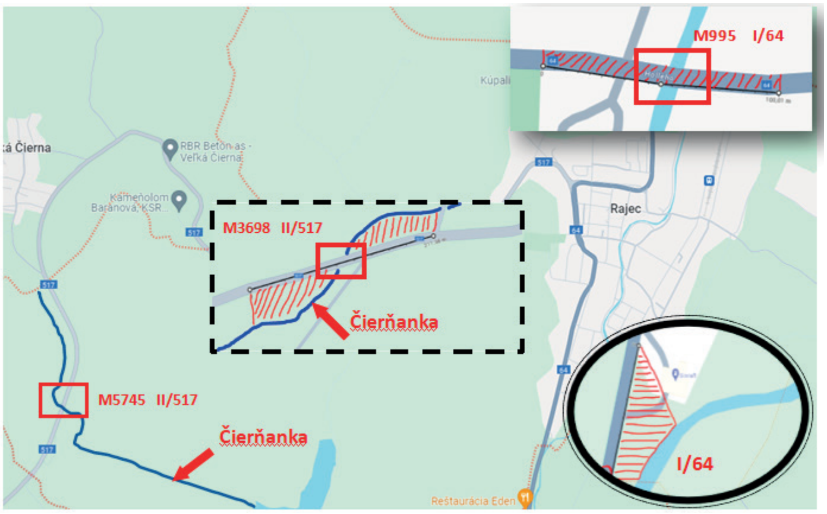

Figure 2 *Representation of parts of the elements near the river (processed by [31])*

II/517 serve to connect the town with the surrounding villages and towns. The significance of the I/64 road also expends to freight transport and supply [27]. The daily traffic characteristics of I/64 and II/517 are shown in Table 8.

There are also road bridges with identification numbers M995, M5745 and M3698. Bridge M995 is located on the I/64 road and bridges the Rajcianka River. Bridges M5745 and M3698 are located on the II/517 road and span Ciernanka watercourse. In addition to the bridges mentioned above, there are two other motor vehicle bridges in the town. However, these are located on local special purpose roads. Table 9 shows all the significant elements of Rajec's transport infrastructure. An example of the characteristics of a selected road infrastructure element required for vulnerability assessment is provided in Table 10.

3.3 Identification of vulnerable road infrastructure elements and parts of them

The criteria in Section 2.1 are used to identify the parts of the road transport infrastructure that are susceptible to the impact of individual events. The assessment of the potential impact of extraordinary events on the territory of the town of Rajec is based on the documents "Analysis of the territory from the point of view of the occurrence of possible extraordinary events of the District Office of the Zilina Region" (hereinafter referred to as the "Territory Analysis") [29], "Zoning Plan of the town of Rajec" [27] and other relevant textual and map documents.

According to the model presented in Section 2.1, the first criterion evaluates the length of the road and the number of road structures located close to the watercourse [18]. For this criterion, a distance of 50 meters or less the watercourse was considered. Flood maps for this area are not available. The representation of the elements near the river is shown in Figure 2.

According to the statistical data of the Ministry of Interior of the Slovak Republic, no flood has been recorded in the territory of Rajec [32]. However, according to the Territory Analysis, the town of Rajec is classified as flood-prone areas. A flood occurred here on the Rajcianka watercourse in 2011 [29].

According to the second criterion, which assesses the features based on their proximity to slopes, contour-based mapping or slope stability maps can by utilized. According to these maps, a 0.75 km section of the II/517 road, constituting 20.16% of the total length in the

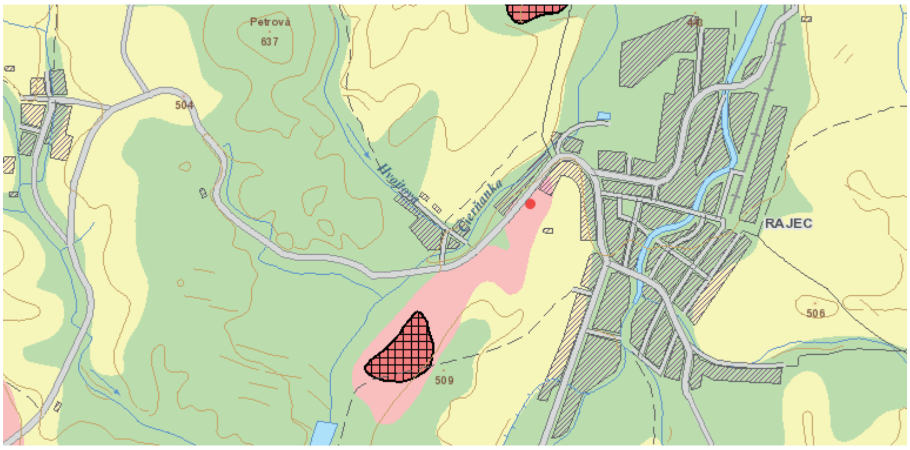

Figure 3 *Map of slope stability in the cadastral area of Rajec [33]*

Table 11 *Resulting vulnerability values by parameter*

Criterion	Parameter	Compliance with the vulnerability criterion
K1	Length of detour route	20 %
	Number of detour routes	25 %
	Full-value compensation	60 %
K2	Bridge length	10 %
	Material of bridge	33 %
	Age of bridge	60 %
K3	Part of TEN-T	0 %
	Part of TEM	0 %
	Part of the international road network „E“	0 %
	The economic significance of transport	80 %
K4	Traffic load	100 %
K5	Slope movements and deformations	1 %
	Floods	10 %
	Torrential rains	1 %
	Technical condition of the dilatation unit	70 %

study area, is particularly susceptible to landslides. An example of a slope stability map of the study area is shown in Figure 3.

For the purposes of assessing the third criterion, mapping documents or geographic information systems can once again be utilized. Among the selected features, the most common in the forested area is the II/517 road. Based on statistical data, no forest fires have occurred in the study area in the recent period [32]. In assessing the criterion for the impact of wind on the road infrastructure, mapping documents from Dlubal Software were employed. According to the map documentation supported by calculations based on technical standards, the territory of the town of Rajec is not located in an area threatened by wind. The same method was used to evaluate the threat of snow calamity. The territory of the town of Rajec falls under Snow Load Area 2, indicating a low risk [34]. These findings are supported by statistical data. No windstorms or snow calamities have been recorded in Rajec from 2013 to 2023 [32].

Since the data on the transport of hazardous substances on the selected routes are not available, the technical condition of the selected bridges M995, M5745, and M3698 were assessed based on the last criterion. These bridges are reported to be in poor technical condition according to available technical data [23].

To illustrate the process of vulnerability assessment of road infrastructure elements, the M995 bridge located on the first-class road I/64 was selected.

3.4 Vulnerability assessment of an element according to criteria and their parameters

Based on the previous characteristics, a vulnerability assessment of the major road infrastructure elements could have been conducted. For the purpose of applying

Table 12 *Lengths of possible detour routes (processed by [31])*

Detour route	Length of the detour route
Povazska Bystrica - Rajec (II/517)	23.5 km
Zilina - Kamenna Poruba - Rajec (I/64-III/2108)	23.2 km
Prievidza - Rajec (I/64)	40.9 km

Table 13 *Resulting values of criteria and overall vulnerability of bridge M995*

Results of individual criteria				
K1	K2	K3	K4	K5
35%	34.33%	20%	100%	20.5%
Resulting vulnerability V= 41.97%				

the modified parameters of the element vulnerability assessment criteria, the M995 bridge was selected. The values of each parameter are shown in Table 11. The individual parameters were calculated according to Equation (1).

From the above evaluations of the individual parameters, it is necessary to describe the parameter "Length of detour route". This parameter considers the significance of the bridge as a means to cross the Rajcianka River for the purpose of travelling to the surrounding area (especially to the city of Zilina) for work. Rajec hosts state forces such as the Police of the Slovak Republic and the Fire and Rescue Corps of the Slovak Republic, along with a polyclinic [31]. Therefore, in the case of damage to the M995 bridge, the basic functionality of emergency services (IZS) would be ensured. Another critical factor is the town's supply of foodstuffs, industrial materials, and fuel for petrol stations. It is assumed that this supply is primarily routed via the I/64 road from nearby Zilina. In assessing the "Length of detour route", parameter Rajec serves as the starting point. Table 12 below shows the detour routes and their respective lengths.

For the purpose of evaluation, the detour route Povazska Bystrica-Rajec (II/517) was chosen as it is a class II road and Povazska Bystrica is a district town. Cars can also use the route via Kamenna Poruba, which however runs along the Class II. road and local special purpose roads.

3.5 Assessment of the total vulnerability of the road infrastructure element

The values of each criterion and the resulting vulnerability of the road infrastructure element are shown in Table 13. The resulting vulnerability of the element was calculated according to the relation 2.

The resulting vulnerability of bridge structure M995 is 41.97%. To determine the vulnerability of the area, based on the road transport infrastructure elements, it would be necessary to calculate the vulnerabilities of the remaining elements. This process would enable identification of the most vulnerable element of the transport infrastructure in Rajec. However, the assessment process itself provides valuable information about the element and its significance, which can serve as a basis for implementing measures.

4 Discussion

Road infrastructure plays a crucial role in functioning of a society and the economy, underscored by its classification as a sub-sector within critical infrastructure. The classification of the road infrastructure element is governed by specific sectoral and cross-cutting criteria. The disruption or destruction of the element would result in widespread negative consequences affecting the operations of the state or a significant part of its territory. However, at the county, city and town levels, there exist several road infrastructure elements that hold social or economic significance for those specific areas.

The aim of this study was to propose an approach for assessing the vulnerability of the road infrastructure elements using validated models. The authors consider the vulnerability assessment of the road transport infrastructure as an integral part of the overall vulnerability assessment of a territory. The overall vulnerability of an area is derived from the vulnerabilities of its constituent elements such as buildings, environment, population, etc. This study presents a potential approach to vulnerability assessment of the road transport infrastructure, using a modified model originally developed for assessing key elements of the railway transport at the Faculty of Security Engineering, University of Zilina.

The presented procedure enables the assessment of vulnerability in individual road infrastructure elements based on freely available data. By employing approaches that are not overly demanding in terms of data collection and availability, it allows for rapid and reasonably accurate results. These results can be informative for the decision-making and further planning in territorial development and crisis management. The criteria and their parameters are well-suited for identifying significant elements of the transport infrastructure. By integrating those criteria into indicators for assessing vulnerability in the road infrastructure elements and their components, based on a societal vulnerability assessment model, it becomes feasible to pinpoint elements more susceptible to emergencies.

The diverse parameters, indicators, criteria, and assessment factors serve as a solid example of how to approach vulnerability or resilience assessments in specific areas. The criteria developed within the models, as adapted in this work, enable swift determination of transport infrastructure vulnerability. Identified vulnerable elements and their parts can subsequently influence the investment decisions, primarily benefiting crisis planning. Outputs from the assessment can facilitate development of evacuation route scenarios that account for the vulnerability of specific transport infrastructure elements. Moreover, they can guide emergency supply planning and the coordination of integrated rescue system components.

This assessment procedure is also applicable within a broader framework of territory risk assessment. Here, the vulnerability of the road transport infrastructure elements contributes to overall area vulnerability, which is a fundamental characteristics of the territory. Together with resilience determination, preparedness, and other features, this approach can comprehensively describe the state of the territory concerning the crisis impacts.

Many variables used to assess the vulnerability of area parts or elements can be expressed or analysed using the spatial data and geographic information systems. In the future research, aimed at comprehensive risk assessments and territory characteristics, like vulnerability or resilience, this approach could prove to be a suitable and valuable tool.

5 Conclusion

The effective models, aimed at identifying and assessing the vulnerability of transport infrastructure were introduced and validated in this paper, and specifically applied and verified within the city of Rajec. By doing so, it was aimed to enhance the general understanding of vulnerability assessment within the road transport infrastructure and underscores its significance in bolstering the territorial resilience. This comprehensive approach not only evaluates the current vulnerabilities but prepares the communities for future challenges, as well. Moreover, the paper introduces the concept of resilience, increasingly acknowledged and applied by researchers to gauge the readiness of regions and individual stakeholders in facing crises. Resilience, as a concept, emphasizes adaptive capacities and the ability to recover swiftly from disruptions, thereby ensuring continuity and minimizing adverse impacts on communities. Through the models presented, the paper provides the readers with valuable insights into utilizing diverse indicators and criteria for assessing the vulnerability of transport infrastructure. Those assessments serve as pivotal components within the broader framework of resilience, contributing to informed decision-making processes and strategic planning for sustainable development. The integration of these models not only enhances the understanding of vulnerability within the transport infrastructure but also lays the groundwork for proactive measures that enhance resilience and ensure the long-term sustainability of urban and regional environments.

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Conflicts of interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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