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INTEGRATING RESILIENCE INDICATORS INTO VIRTUAL OPERATIONS SUPPORT TEAM FOR ROAD CRITICAL INFRASTRUCTURE IN CRISIS MANAGEMENT

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Resume

Increasing disaster frequency intensifies the need for rapid, location-specific information in crisis management. A Virtual Operations Support Team (VOST) can enhance situational awareness by verifying open-source data, but these outputs are rarely transformed into resilience indicators. In this paper is presented a framework that maps verified VOST outputs and metadata to indicators for road critical infrastructure resilience and links them to the crisis decision cycle. A preliminary test on media data (1 Aug-31 Dec 2024; $n = 2,045$) confirmed a stable baseline and clear peaks usable for management-defined thresholds and trigger actions. The framework also outlines governance, supplier interfaces, and GIS-based operationalization of Exposure, Condition, Accessibility, and Consequence.

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1 Introduction

According to the World Disasters Report, approximately 631 disasters occur on average each year [1]. The increasing frequency and severity of these events raise demands for rapid, accurate, and spatially specific information for crisis management stakeholders. In situations where the effective management of emergencies is constrained by personnel and capacity limitations, the involvement of digital volunteers can synergistically support crisis management activities. Digital volunteers collaborate online and can improve decision-making by collecting, evaluating, analysing, and verifying crisis-related information from Twitter, Facebook, or YouTube [2]. At the same time, social media and the rise of volunteer and technical communities (V&TC) have changed approaches to handling spatial data in crisis analysis. In response, a new form of organised effort for collaborative information collection and community management has been introduced. It is referred to as Virtual Operations Support Teams (VOST). This concept creates a framework for the systematic linkage of formal crisis management bodies

with digital volunteers. However, its implementation has so far remained limited to only a few cases [2].

The VOST-verified data used in crisis management include metadata from geolocation, infrastructure, health, logistics, humanitarian, and meteorological domains. They include both precise quantitative information, such as GPS coordinates, numbers of people, capacities, and status and volume indicators, and qualitative descriptions and multimedia records, such as text messages, photographs, and satellite imagery. The data are dynamic and temporally variable. They are produced both as structured records and as unstructured information streams from the online environment. A key feature is the varying level of verification and reliability. This ranges from official reports by crisis management authorities to unverified content and potential misinformation from social media, which require systematic verification. Once processed and verified, these data and metadata can provide crisis management with a multidimensional real-time picture of the situation and support early threat identification, decision-making, and measures to increase the resilience of critical infrastructure [3]. A major limitation, however,

remains the response time of such information, as current approaches often do not enable the sufficiently rapid identification of the origin of a disruption, the monitoring of its development, and the validation of its local or cascading impacts in real time.

The VOST has the potential to strengthen the information support available to decision-making bodies and to enable more effective coordination among crisis management stakeholders. Its integration into operational management processes can benefit crisis communication and resilience mapping. Although the benefits of VOST have already been demonstrated abroad, the system is currently implemented in only a limited number of countries and it is not yet in place in the Czech Republic. Even where it has been introduced, the use of the monitored data remains limited. These data are often used only to verify information that is generally already known, and the collected data are not systematically used to indicate disruptions in service functionality, network accessibility, or resilience [4].

Despite these benefits, there is still no methodologically integrated framework that would connect, in real time, the identification of deviations in the road network functioning, their independent verification from open sources, and their translation into indicators applicable to crisis management. Current approaches usually focus either on the verification of individual pieces of information or on resilience indicator systems, but without their systematic integration in the environment of road critical infrastructure. At the same time, under the conditions of the Czech Republic, there is no operationally embedded procedure that would elaborate this linkage in organisational and methodological terms.

Indicators are a widely used tool for the timely detection of potential disruptions to the resilience of critical elements and for the continuous assessment of the current situation as well as the actual state of the environment. Monitoring the values of selected indicators over time enables the anticipation of future developments and the timely adjustment of implemented measures.

In the context of such indicators, using data for resilience mapping represents a key extension of disaster prevention. Network metrics can be translated into measurable indicators of infrastructure topology and operation, and they help to identify critical links, nodes, and corridors within the system [5]. Management can use these outputs to prioritise interventions, plan redundancy, and support operational traffic management. These metrics can also be applied to the assessment of communication processes and data flows, for example by monitoring the network availability, density, and latency, or by identifying key nodes within the information system.

Building on the above relationships, the methodological dimension of the paper focuses on approaches applicable to disruption indication and

resilience mapping based on data verified through VOST [6]. Particular emphasis is placed on methods that enable verified outputs to be translated into comparable indicators applicable within the road infrastructure environment. Examples include travel time reliability analysis and the Planning Time Index (PTI), geoinformation-based approaches to identifying critical sections of the transport network, methods for determining hydrologically sensitive road sections prone to flash flooding, and the assessment of technical condition through the Pavement Condition Index (PCI).

The need for new assessment approaches follows from the fact that the resilience of road critical infrastructure is affected by uncertainty, data heterogeneity, and dynamically changing operating conditions. Assessment must therefore integrate multi-source data, reflect the spatio-temporal variability of the observed phenomena [7], and enable identified changes to be translated into indicators applicable to decision-making. This requirement supports the adoption of approaches that link standardised infrastructure assessment with operationally acquired data and create a robust framework for resilience assessment [8].

In this paper is given a response to this gap in three ways. First, the VOST activities are defined in relation to disruption indication and the resilience mapping of road critical infrastructure. Second, a framework is proposed that links verified open-source data and metadata with indicator-based assessment applicable to the operational and tactical levels of crisis management. Third, the possibility is demonstrated for establishing a reference level, identifying deviations, and linking them to threshold values and trigger actions in a time-critical environment.

Based on the relationships outlined above, the paper aim was to define the VOST activities and develop a framework for using the verified data and metadata in resilience mapping within the road infrastructure subsector. Achieving this objective is intended to support the establishment of a data framework applicable to early threat identification, decision support, and the planning of measures aimed at increasing the resilience of critical infrastructure [9].

2 The VOST concept and implementation background

A Virtual Operations Support Team (VOST) is an organised form of volunteer support that strengthens the capacity of crisis management authorities in the online environment. It responds to the growing importance of social media during emergencies by converting spontaneously shared citizen-generated data into outputs applicable to management and decision-making [10]. VOST consists of trained volunteers working remotely who are integrated into formal structures and coordinated by crisis management authorities.

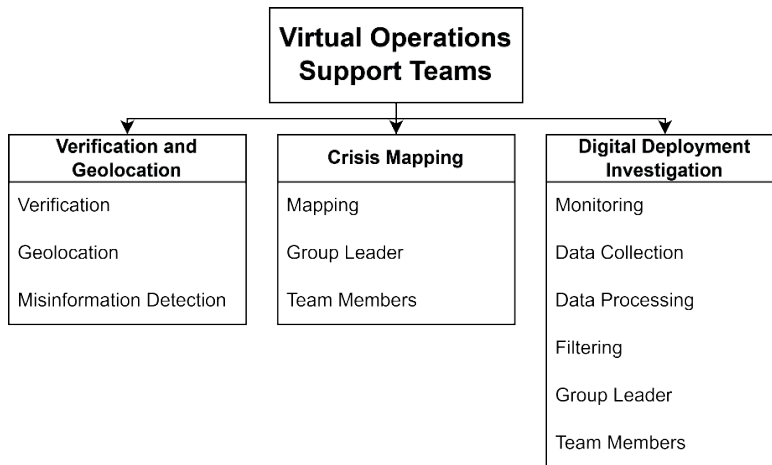


Figure 1 Main areas of the Virtual Operations Support Team

Affiliation			
Citizen / Public	Affected Citizens	Digital Volunteers	
	Emergent Groups	Virtual and Technical Communities	
Authority	Incident Force	Community Scout	
	Incident Management Teams	Virtual Operations Support Teams	
Realm		Real	Virtual

Figure 2 Typology of actor roles in the real and virtual environment during emergencies

In practice, however, its systematic implementation within national crisis management structures remains limited because the specific activities, outputs, and implementation steps of VOST have not yet been defined with sufficient clarity.

while maintaining requirements for accuracy and reliability [11]. To fully use the potential of digital volunteers, an integrated approach is also necessary, within which the crisis management authorities not only accept these activities but coordinate them, as well.

2.1 Defining the VOST tasks

The VOST tasks can be structured into three consecutive areas that correspond to the core functional domains shown in Figure 1. The first area is verification and geolocation, including authentication of content, identification of misinformation, and determination of the time and location of the report [11]. The second area focuses on crisis mapping, that is, the sorting, spatial organisation, and visualisation of relevant data in the form of aggregated and standardised outputs for operational components of crisis management.

The third area represents the digital deployment investigation, which includes monitoring, systematic data collection, and their basic processing, filtering, and preliminary classification by topic and location [11]. Performing these tasks requires adequate organisational and staffing capacity and the ability of management to flexibly integrate information from informal sources

2.2 Typology of social media actor roles and the position of VOST

The typology of social media actor roles during emergencies provides an appropriate framework for defining the position of VOST within the crisis communication system. An overview of these roles is summarised in Figure 2. The role matrix presented by Fathi et al. [2] offers a differentiated view of behavioural patterns by distinguishing between actors operating in the real and virtual environments and, at the same time, by separating institutional actors, that is, public authorities and organisations, from citizens. This distinction is important for understanding that VOST does not represent an isolated volunteer activity, but rather a specific interface between the formal crisis management structures and the dynamic digital environment.

In this typology, VOST is classified among

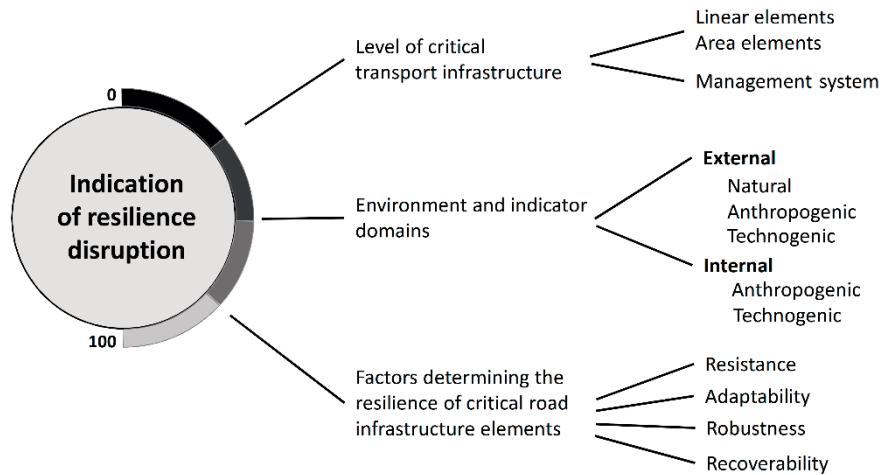


Figure 3 Framework for indicating disruptions to the resilience of critical infrastructure elements

institutional organisations operating within public authorities, even though it relies on volunteer capacity and operates predominantly in the virtual environment. As an organisational unit, it cooperates at the inter-institutional level with incident management teams and other components responsible for situation analysis and the operational response to an emergency. VOST therefore does not function merely as a technical intermediary for data handling, but as an operational interface between the official crisis management structure and the dynamic environment of social media.

The literature also highlights efforts by VOST to cooperate with other VOST teams and volunteer and technical communities (V&TC) in joint deployments, typically during large scale or cross-border events. However, the requirements for effective cooperation between the formal humanitarian and crisis response organisations and Volunteered Geographic Information (VGI) communities' place considerable demands on coordination. Challenges arise particularly in the standardisation of data and procedures and in the allocation of accountability [12]. This broadens the standard operational framework of VOST and at the same time indicates the potential of further specialisation of its activities. One such specialisation may be a branch of VOST focused on resilience mapping, which can contribute to strengthening society by supporting prevention, preparedness, adaptability, and recovery, as described by Rehak et al. [13] and Ryska [14].

This development confirms the growing importance of coordinated cooperation between the formal crisis management structures and digital volunteers and is at the same time consistent with the direction of the European regulatory framework, in particular Directive (EU) 2022/2557 of the European Parliament and of the Council [15]. At the same time, the use of data mining and machine learning concepts has accelerated the availability and evaluation of VGI and other data related to disaster response [16]. Even so,

it remains difficult to align social media data clearly with users' information needs, because the usefulness of information varies according to their roles and objectives within the disaster response [16]. VOST must therefore not only process data technically, but also continuously adapt its outputs to the changing information needs of crisis management.

2.3 Framework for implementing indicators

The literature describes several metrics and approaches for assessing the resilience of critical infrastructure. Both quantitative and qualitative methods are used, as well as empirical approaches based on data or hypothetical scenarios. However, those methods often face limited availability of information and data [17], subjectivity in the responses provided, dependence on a specific type of infrastructure [18] or on the event scenario, and a limited ability to generalise the results [19].

For these reasons, an indicator-based approach appears to be a suitable direction for implementing a systematic framework for resilience assessment based on a set of measurable indicators. These indicators make it possible to track changes over time, compare different critical infrastructure elements, and support management decision making.

A fundamental prerequisite for the proper functioning of a procedure for indicating disruptions to the resilience of critical infrastructure elements is the clear definition of the framework within which indicators are defined and applied [20]. This framework is illustrated schematically in Figure 3.

The essence of the framework lies in defining the baseline conditions for specifying the key characteristics of indicating disruptions to the resilience of critical infrastructure elements. Splichalova et al. [21] and Patman et al. [22] distinguish four interrelated levels:

1. Levels of critical infrastructure: individual elements, systems, and networks whose functionality is subject to assessment.
2. Environment and indicator domains: the context in which the infrastructure functions, including the physical, social, and institutional environment, as well as the thematic domains of indicators.
3. Factors determining the resilience of critical infrastructure elements: internal and external factors that influence an element’s ability to withstand disruption and restore its functions.
4. Database of resilience disruption indicators: a structured set of indicators, including their definitions, units, data sources, and links to the assessed factors.

Leading indicators reflect conditions and factors that precede a disruption, for example the level of preparedness, maintenance quality, or the degree of dependence on critical suppliers. They allow for management to take preventive action.

Lagging indicators describe impacts that have already occurred and changes in performance over time, for example outage duration, capacity loss, or recovery speed. They are used mainly to assess consequences and the effectiveness of recovery [23].

In this context, the resilience is understood as an overarching concept that links indicators of risk, safety, protection, business continuity, and operational performance [24]. For the purposes of this paper, however, it is operationalised primarily through indicator-based assessment related to road critical infrastructure and to data verified through VOST. This creates a direct conceptual transition between the general resilience framework and the subsequent verification of information flow dynamics for the purposes of the indication framework.

2.4 Verifying the dynamics of the information flow for the indication framework

Resilience mapping of the road critical infrastructure requires a standardised description of deviations from normal conditions and their interpretation in time and space [25]. Indicator systems, including leading and lagging indicators, provide a tool for linking operational observations with the assessment of preparedness, response, and recovery of provided services. For their use in crisis management, the ability to identify a change from a reference level, that is, the baseline, in a timely manner is crucial. It is also necessary to verify its cause so that management can set escalation thresholds and corresponding intervention procedures. Without this link, resilience mapping remains fragmented and limited to partial data sources.

To support the setting of threshold values and escalation rules, the dynamics of the information flow were verified using media data. A preliminary analysis of the sectoral classification of reports led to selection of the transport and logistics sector for the initial construction and validation, with implementation focused on the dominant road transport subsector. Content analysis of media outputs indicates a dominance of transport and logistics topics with 12,522 reports, followed by construction with 7,508 reports, IT and communications with 5,347 reports, sport with 4,529 reports, health with 2,824 reports, culture and education with 1,925 reports, and agriculture with 1,493 reports. With regard to channels, the internet dominates with 68.0 % and 32,281 reports. It is followed by social media with 11.6 % and 5,530 reports, print media with 8.6 % and 4,067 reports, radio with 7.6 % and 3,613 reports, and television with 4.2 % and 1,997 reports.

To verify the temporal variability, the daily number

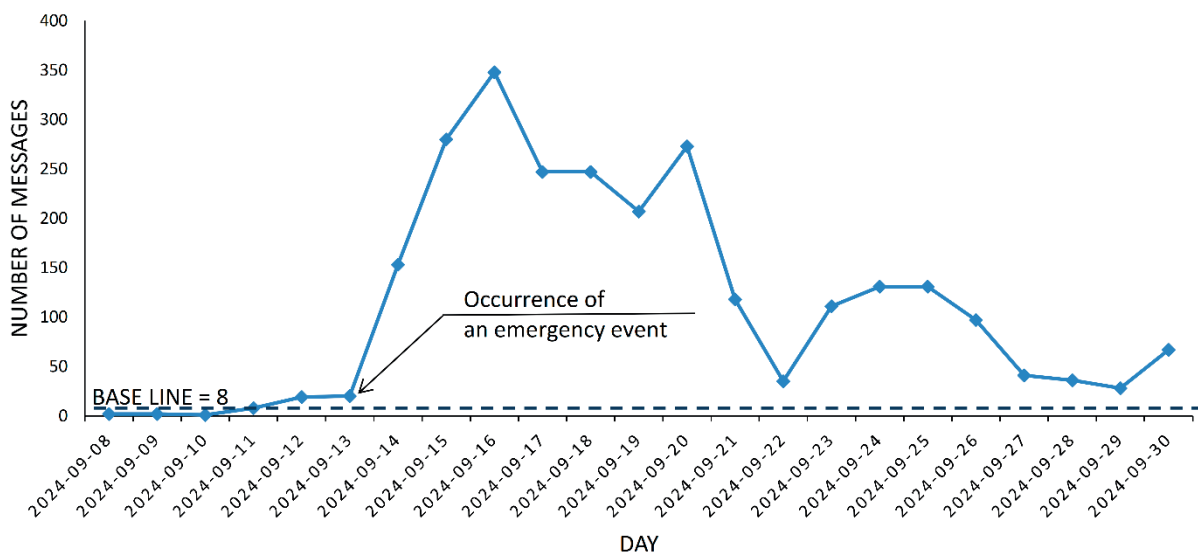


Figure 4 Daily aggregation of reports for the transport and logistics sector with a focus on the road transport (1 August 2024 to 31 December 2024)

of published reports was aggregated for the period from 1 August 2024 to 31 December 2024 (n = 2,045, see Figure 4). The time distribution shows a peak during 15 to 19 September 2024, when 729 reports were published, which represents 35.6 % of the total volume. The maximum occurred on 16 September 2024 with 197 reports. It was followed by 15 September with 169 reports and by 17 to 19 September with 111 to 134 reports. Outside the peak period, the volume stabilises at a low level, with approximately 1 to 2 reports per day in August, which represents the baseline. After the peak, a gradual decline predominates.

The identified dynamics can be used to set an indication framework in a time critical environment. The framework uses the baseline as the reference level and escalation thresholds defined by a combination of report volume, geolocation, and event typology. These thresholds and the related trigger actions are set by management with regard to tolerated risk, system capacity, and the required response speed. In this way, the VOST supports not only the verification of individual events, but the continuous trend evaluation and timely escalation of intervention, as well.

3 Synergy between the VOST and indicator systems in crisis management

Synergy between the Virtual Operations Support Team (VOST) and indicator systems in crisis management lies in converting verified VOST outputs from open digital sources into quantitative and qualitative resilience

indicators applicable to the assessment of road critical infrastructure resilience. This complements traditional indicators that rely mainly on historical data or expert judgement and strengthens management’s ability to respond to dynamic developments. VOST outputs cover a wide range of data types. They include geolocation and geospatial data for locating hotspots and refining map layers, and infrastructure reports that can indicate passability, service availability, and the functionality of nodes within road critical infrastructure. They also include meteorological and environmental data that support early warning, health and humanitarian information that can be used for prioritising resources and capacities, satellite and aerial imagery for damage assessment and verification of visual content, and aggregated mobile data for mobility and exposure indicators [26]. In addition to the content itself, metadata are also an important source for indicators. Examples include reporting frequency, temporal distribution, platform type, linguistic characteristics, and sharing intensity. These attributes describe the crisis dynamics, the level of information noise, and the effectiveness of communication measures. After the filtering and verification, VOST data and metadata can be mapped directly to indicators or used as a supporting layer [11].

3.1 Conceptual model for indicator-based resilience evaluation

To use VOST outputs within indicator systems, it is necessary to map them to indicators that correspond to

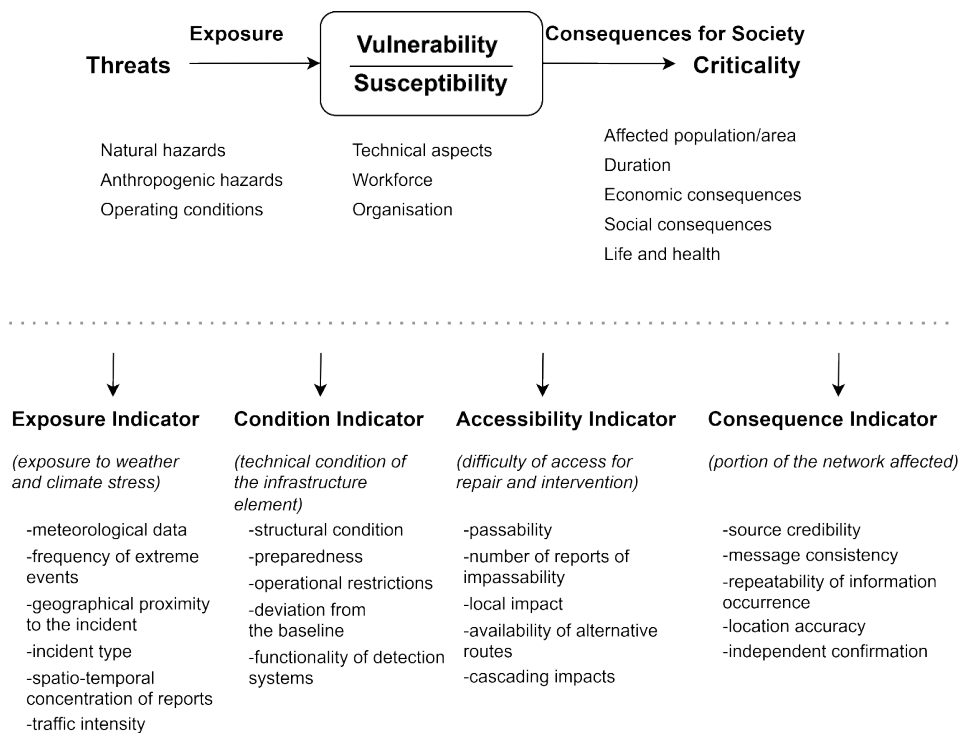


Figure 5 Resilience indicator model for the road critical infrastructure

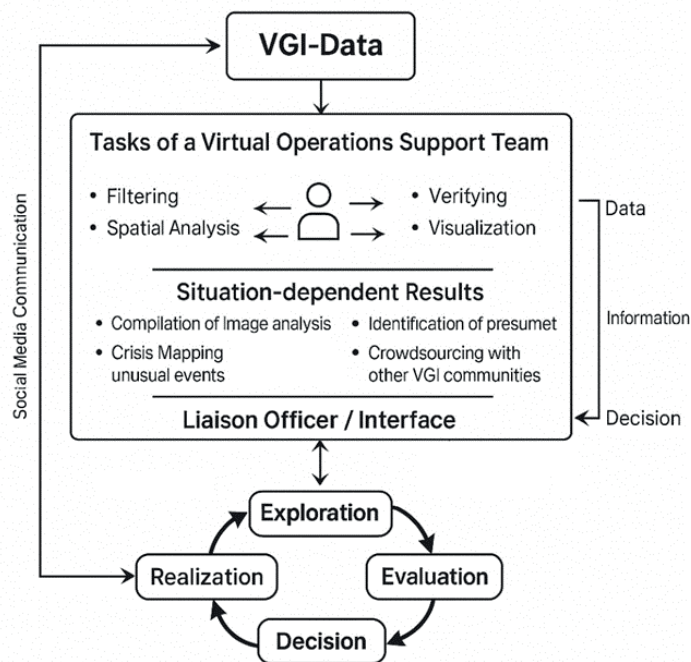


Figure 6 VOST data flow in crisis management

the link between Threats, Exposure, Vulnerability and Susceptibility, Consequences for society, and Criticality (Figure 5). In the first part of the chain, threats enter the exposure indicator, which describes the degree to which an infrastructure element is exposed to hazardous phenomena, for example weather and climate related stress. Next, vulnerability and susceptibility are represented primarily by the condition indicator, which captures the technical state of the element, and the accessibility indicator, which reflects the difficulty of access for intervention and repair. Those characteristics are followed by consequence indicators that capture the extent of impacts within the network, for example the size of the affected area or the affected part of the network. Criticality is derived from the combination of network impacts and their significance for society. It provides a basis for prioritising measures and for crisis management decision making within the situational overview.

3.2 Implementing resilience indicators into the crisis management decision cycle

An integrated process connecting incoming VGI data with the crisis management decision cycle is illustrated in Figure 6. The VGI data from social media enter VOST, where filtering, spatial analysis, verification, and visualisation are performed. The outputs take the form of situation dependent products, for example crisis mapping, image-based analyses, and the identification of unusual events. They are then transferred through a liaison officer to the exploration, evaluation, decision,

and realisation cycle. In this paper, the framework is extended by converting verified outputs into indicator systems for the resilience of road critical infrastructure in order to provide a comparable basis for operational and tactical management.

At the operational level, indicators enable the setting of threshold values. Exceeding these thresholds initiates predefined trigger actions. Examples include closing of a road segment, rerouting traffic, activating detours, reinforcing Integrated Rescue System units, or changing response priorities in locations with a high concentration of damage reports. Indicators also support continuous updates of situational maps and operational plans based on real time information on passability, weather conditions, impact extent, and population mobility. Decision making also reflects links to supplier entities, in particular equipment availability, response times, backup capacity, and constraints during service restoration.

At the tactical level, indicators and their time series are used to evaluate the effectiveness of the response and to identify the recurring network weaknesses. These are typically lagging indicators of performance loss and recovery, the extent of damage, and recovery time. The outputs make it possible to derive structural vulnerabilities, including dependencies on key nodes and specific suppliers, and to translate them into investment planning, updates of business continuity plans, and the design of standard measures to increase resilience [17].

Threshold values and the definition of trigger actions are set by management with regard to tolerated risk, system capacity, responsibilities, and the legal framework. Some indicators are derived from data

with higher uncertainty, such as crowdsourcing and social media. For this reason, it is appropriate to work with record credibility levels, triangulation rules, and weighting in decision models. Integrated use of VOST and indicator systems therefore supports the management of a specific event and the long term strengthening of the resilience of road critical infrastructure and related services in the supply chain.

To illustrate the practical application of the proposed framework, a model situation can be considered in which a hydrometeorological event causes disruption to the function of a bridge structure or an adjacent section of the road network. The first step is the detection of an anomaly, that is, a deviation from normal conditions, for example a sudden increase in relevant media reports or geolocated records of impassability. In line with the proposed procedure, this triggers the creation of a candidate event record. VOST then initiates the collection and preprocessing of data from the open digital sources, in particular social media, online news reports, map applications, and supplementary meteorological sources. At this stage, the preliminary elimination of information noise is performed, based on basic linguistic analysis of keywords, filtering by location, time, content type, and language, deduplication of records, and basic normalisation of metadata. This step enables the rapid narrowing of the data stream to records with potential relevance for crisis management decision-making. In the second step, the candidate information is verified and enriched. VOST assesses source credibility, message consistency, repeatability of the information, and independent confirmation across multiple channels, adds geolocation, and assigns the record to a specific network element and its operational context.

In the third step, the verified records are translated into indicators. Hydrometeorological loading enters the Exposure indicator, technical condition and operational impairment enter Condition, reachability for intervention and detour options enter Accessibility, and network as well as societal impacts enter Consequence. These indicators are then compared to the reference baseline and with threshold values defined by management. An empirical anchor for this logic was provided by the analysis of media data for the transport and logistics sector for the period from 1 August 2024 to 31 December 2024 ($n = 2,045$), in which a stable baseline of approximately 1-2 reports per day and a marked peak during 15-19 September 2024 were identified, with a total of 729 reports and a maximum of 197 reports on 16 September 2024. Exceeding the thresholds then activates the corresponding trigger actions, such as traffic restriction, designation of a detour route, prioritisation of technical intervention, or reinforcement of Integrated Rescue System units. The model situation therefore shows that the proposed framework is not merely a conceptual construct, but can be used for early disruption indication, situational overview, and support for operational as well as tactical decision-making.

3.3 Resilience of road critical infrastructure within an indicator framework

In the road transport subsector, resilience should be assessed as a systemic property arising from the interaction of the exposure of infrastructure elements, their vulnerability/susceptibility, the consequences of disruption, and criticality within the network [27]. Within this framework, vulnerability and susceptibility do not represent concepts interchangeable with resilience, but rather its partial analytical dimension expressing the proneness of elements to degradation, loss of functionality, and loss of performance under the action of threats. Lagging indicators capture already manifested impacts and the current loss of system performance, whereas leading indicators indicate conditions preceding disruption and enable its further development to be anticipated [27]. At an aggregated level, indicators therefore serve not only to describe the current vulnerability of the system, but also to assess trends relevant to the evaluation of its resilience [28]. The construction of indicator systems must therefore be based on a coherent theoretical framework and a systematic indicator development process [13]. The road infrastructure should at the same time be modelled as a network of elements and flows in which criticality is determined not only by the technical condition of individual elements, but also by their role within the network, the existence of alternative routes, and links to other transport modes and supply chains [29]. A framework defined in this way provides the basis for indicator selection and for management decisions on monitoring, maintenance, and investment priorities.

For the operational use of the proposed framework, it is also necessary to define how VOST is structurally and procedurally integrated into decision-making in time-critical environments. In performing its tasks, VOST works with heterogeneous VGI data and other open sources, in particular for the purposes of filtering, verification, and interpretative processing of information. In the conditions of the road transport subsector, this procedure should therefore be further extended through the integration of indicator systems that enable verified outputs to be translated into decision-support inputs applicable to monitoring, escalation, and the subsequent evaluation of resilience.

Proposed procedure:

- Definition of target indicators for the road critical infrastructure: Management, in cooperation with infrastructure experts and data analysts, defines a structured set of leading and lagging indicators relevant to individual phases of the resilience cycle and at the same time to the key dimensions of the assessment, in particular exposure, condition, accessibility, consequences, and criticality. Examples include indicators of passability, structural condition,

maintenance preparedness, and the functionality of detection and communication systems, as well as the continuity of provided services.

- Mapping the VOST outputs to indicators: For each indicator, it is necessary to specify which types of data and metadata VOST can provide and what informative value they have for its construction or updating. These may include, in particular, geolocated reports of impassability, metadata on reporting intensity, information extracted from photographs and videos, and supplementary data on weather, event extent, or the humanitarian situation. The mapping must at the same time distinguish whether individual outputs enter indicators of exposure, condition, accessibility, consequences, or criticality, and must take into account their temporal validity, level of verification, and spatial accuracy.
- Integration into the data pipeline: VOST transfers verified data and metadata into a centralised indicator database in which they are normalised, aggregated, and subsequently interpreted for the purposes of the situational overview. The responsible unit, for example the road authority or the crisis staff, ensures the operation of tools for indicator calculation, updating, and visualisation. It is essential that this data pipeline support the continuous transfer of verified outputs into the decision-making process while also enabling their linkage with other relevant data layers.
- Setting roles and responsibilities: The governance framework must clearly define who approves the indicator methodology, who is responsible for VOST operations, who interprets the results, and who makes decisions. It also includes the delineation of interfaces with supplier entities, including ICT, data, and maintenance. A clear allocation of roles and responsibilities is necessary to ensure the consistency of outputs, accountability for their use, and continuity between operational and tactical management.
- Feedback and learning: Results obtained from the use of indicators during the real events must be systematically evaluated and used for the continuous updating of the indicator database, VOST configuration, and institutional relationships with supplier entities. This mechanism closes the adaptation and learning cycle of the proposed framework and at the same time supports its long-term validity and operational applicability.

For indication at the level of the road critical infrastructure subsector, it is appropriate to use a combination of indicators representing exposure, conditions, accessibility, and consequences. This approach captures both leading indicators, meaning early warning signals of deteriorating conditions, and lagging indicators, meaning indications of already manifested failures and their consequences

at the level of system performance [30]. Although an analogous categorical structure has also been used in other critical infrastructure sectors [28], in this paper it is adapted specifically to the conditions of road infrastructure and to the informational capacities of VOST.

- Exposure: The exposure indicator expresses the degree to which an element of road critical infrastructure is subjected to natural and anthropogenic threats. It is determined based on the spatial and operational data, in particular on flood-prone areas, slope instability, locations susceptible to icing, traffic intensity, heavy vehicle loading, or incident frequency. The result is a normalised exposure score that can be used as a leading indicator for the early identification of an increased risk of disruption.
- Conditions: The condition indicator expresses the technical and operational state of an element of the road critical infrastructure based on diagnostics, inspection, and maintenance data. In the road infrastructure context, it may be derived, for example, from pavement condition indicators, assessments of bridge structures, or partial indicators of evenness, skid resistance, load-bearing capacity, and material degradation. The result is the translation of these findings into a unified scale that enables comparable evaluation of technical condition across the network and serves as a key input for estimating vulnerability/susceptibility.
- Accessibility: The accessibility indicator expresses the reachability of an element of the road critical infrastructure for intervention, maintenance, and the restoration of its function. It is derived from network topology and response conditions, in particular from road category, the existence of detour routes, constraints on heavy equipment, travel times of maintenance units or Integrated Rescue System components, and the current passability of the affected area. The result is a comparable measure of accessibility that makes it possible to assess how quickly and under what constraints a disrupted element can be addressed.
- Consequence: The consequence indicator expresses the extent and severity of the impacts of failure or functional limitation of an element of the road critical infrastructure on mobility, territorial accessibility, economic activity, and the provision of essential services. It is derived primarily from the position of the element within the network, traffic intensity, the importance of the served area, and links to critical entities such as hospitals, industrial zones, logistics hubs, or Integrated Rescue System components. The result is a comparable measure of consequences that makes it possible to assess the societal and operational significance of the disruption.

An analogous framework can be applied to road infrastructure by using geoinformation technologies. In a GIS environment, Exposure can be derived as a combination of spatial layers representing natural and anthropogenic threats, for example floodplains, slope instability, icing prone locations, heavy vehicle loading, and incident intensity. Condition can be derived from diagnostics and inspections, for example pavement conditions indices such as PCI, assessments of bridge components, and indicators C1 to C4 for evenness, skid resistance, load-bearing capacity, and degradation, converted to a unified scale. Accessibility is derived from network topology and response conditions, including road categories, detour options, constraints on heavy equipment, and travel times of maintenance units or the Integrated Rescue System. Consequence combines the importance of an element within the network, for example its inclusion in backbone corridors and its function within the Trans European Transport Network, transport volumes, and links to critical entities such as hospitals, industrial zones, and logistics hubs. It therefore expresses the network and societal significance of disruption.

Indicators can be derived from operational and maintenance databases, for example congestion frequency, the Planning Time Index, and closure durations, and also from expert assessment of supporting materials such as hazard maps and the strategic importance of a corridor. Subsector management defines threshold values, assessment periodicity, and links to decision-making processes such as maintenance plans, investments, and crisis plans, while taking into account dependencies on supplier entities. From the perspective of resilience assessment, continuity between the leading indicators, including exposure, conditions, and accessibility, and lagging indicators, including capacity loss, congestion extent, recovery time, and incident severity, is essential. Aggregation proceeds vertically from the asset level through corridors and the network, and horizontally into composite indicators for threat scenarios. Weights can be adjusted according to the event type, for example flooding compared to excessive loading, which supports comparability and transparent management decision-making [31].

4 Conclusion

The aim of this paper was to propose a framework that links the activities of a Virtual Operations Support Team (VOST) with indicator systems for the assessment of critical infrastructure resilience and to verify its applicability in the road transport subsector. The paper is based on a literature review of the concepts of VGI, V&TC, and VOST, as well as indicator-based approaches to resilience. It is a response to the need to translate verified information from open digital sources into

comparable indicators that can be used directly in crisis management decision-making.

The results show that the VOST provides a systematic source of structured and unstructured data and metadata with a spatiotemporal reference that can support both leading and lagging indicators. Verification of information flow dynamics using media data for the transport and logistics sector confirmed the presence of a stable reference level, that is, the baseline, and distinct peak periods. These findings support the design of threshold values and escalation rules, which are defined by management with regard to tolerated risk and system capacity. The benefit of VOST becomes particularly evident in time critical phases when formal data sources do not provide sufficiently rapid and interpretatively clear information about the nature of the disruption and its impacts on the functioning of elements within the road network and the services they provide.

In the paper is also presented a conceptual model for mapping indicators across the links among threats, exposure, vulnerability/susceptibility, consequences, and criticality and for connecting this model to the procedural framework of VOST and the crisis management decision cycle. For the road transport subsector, the paper describes the operationalisation of the categories of Exposure, Conditions, Accessibility, and Consequence in a GIS environment and their aggregation to the level of assets, routes, corridors, and the network. The framework is complemented by an implementation procedure for integrating indicators into the VOST system, including the delineation of roles, responsibilities, interfaces with supplier entities, and a feedback mechanism. This creates a basis for linking operational event indication with tactical impact evaluation and strategic planning of measures aimed at increasing resilience.

The proposed approach is subject to limitations arising from the nature of open data. Further limitations are related to the elimination of information noise in such data. In the current framework, noise reduction is based primarily on basic linguistic analysis of keywords, filtering by location, time, content type, and language, deduplication of records, and basic normalisation of metadata. This procedure enables basic data preprocessing, but it is not yet fully sufficient for the rapid responsiveness in a time-critical environment. Practical implementation therefore requires the standardisation of verification procedures, more precise linguistic and contextual processing, the establishment of a governance framework, and clarification of the legal and ethical conditions for data handling. Real-world deployment also depends on organisational and staffing capacity, the availability of trained VOST members, data-analytic capability, and the level of trust between institutions and volunteer communities.

Further research should focus on pilot testing of the framework under Czech conditions for selected types of incidents on the road network, validation of threshold values and trigger actions using real events,

and linking VOST outputs with formal data sources of infrastructure operators. It should also focus on refining the mechanisms for eliminating information noise, which in the current framework are based mainly on basic linguistic analysis of keywords and simple filtering. To improve responsiveness, it is necessary to extend this procedure through more advanced linguistic and contextual processing of records and through metrics of record quality and credibility for indicator weighting. These steps would strengthen the usability of the framework for crisis management decision-making and support the long-term increase of the resilience in road critical infrastructure and related services.

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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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