

Structure-conditioned vulnerability of road networks under flood and landslide disruptions: evidence from Central Java, Indonesia

Berlian Kushari^{a,b,*}, Muhammad Isran Ramli^a, Bambang Bakri^a, Ardy Arsyad^a

^aDepartment of Civil Engineering, Hasanuddin University, Gowa 92171, Indonesia

^bDepartment of Civil Engineering, Islamic University of Indonesia, Sleman 55584, Indonesia

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Abstract

The vulnerability of road networks under disaster conditions is typically discussed in terms of hazard exposure. However, the impact of network structure on the consequence of disruption remains an under-explored area. The present paper examines the effect of road network structure on the degradation of connectivity under disruptions caused by floods and landslides. This is achieved through a graph-based analytical framework, with a representative empirical testbed: the primary road network of Central Java, Indonesia. The network is modeled as a graph and the segments at risk of hazard exposure are identified using spatial overlay. These segments are then systematically deleted based on hazard type, hazard level and spatial localization scenarios. The performance of connectivity is measured based on the largest connected component, the average shortest path length and global efficiency. These measurements are taken both with and without the integration of toll roads. The results obtained demonstrated the presence of disruption signatures, each of which is unique to each hazard. Despite the considerable spatial extent of disruptions, the disruptions caused by flooding result in a gradual degradation of the network in view of redundancy. Conversely, landslide-induced disruptions are spatially small, but they have a disproportionate effect on structurally critical links, thereby causing fragmentation. In addition, the integration of toll roads does not necessarily enhance the robustness of the network when dealing with disruption, indicating an alteration in the structural dependency of the network. These findings support a reframing of road network vulnerability as a structure-conditioned response to disruption, highlighting the significance of structural robustness in infrastructure planning beyond conventional connectivity-based assessments, thereby supporting more effective infrastructure planning and risk mitigation strategies.

Keywords: Road network vulnerability; graph theory; disruption analysis; multi-hazard; structural robustness

1. Introduction

Road networks constitute critical infrastructure systems that facilitate regional mobility, logistics, and emergency response, particularly in hazard-prone regions [1,2]. Under disruptive events, the failure of a relatively small number of road segments can result in disproportionate connectivity loss, a phenomenon widely discussed in network robustness and vulnerability studies [3,4]. The impact of such phenomenon is governed not only by the spatial extent of hazards but also by the structural organization of the network. In this sense, road network vulnerability is not solely an outcome of external disturbances but is intrinsically conditioned by network topology.

Existing studies on road network vulnerability have predominantly focused on exposure-based and performance-oriented approaches, including accessibility loss, travel distance changes, and connectivity degradation [5,6,7,8]. These

approaches have been applied to assess the impacts of flooding, extreme weather, and other disruptions on transport performance [7,9]. While these studies offer valuable insights into system performance under disruption, they tend to frame vulnerability as a direct consequence of hazard occurrence. From a structural perspective, however, hazards do not generate vulnerability independently; rather, they reveal latent fragility embedded within the network. The criticality of a road segment arises is not merely a consequence of its exposure to hazards, it is also a result of its structural role in maintaining network connectivity.

This perspective assumes particular relevance in regional networks where redundancy is unevenly distributed and where structural dependence on specific corridors is high [4,10]. Different hazard types may exert an effect on network connectivity through fundamentally distinct structural mechanisms. Flood-induced disruptions are typically characterized by spatial extent and progressive degradation across multiple links [7], whereas landslide-induced disruptions are frequently localized but may affect structurally critical links, resulting in abrupt fragmentation. Recent studies

* Corresponding author. Tel.: +62-81326013378

Email: bkushari@uii.ac.id

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have increasingly emphasized the importance of understanding disruption patterns and network resilience under multi-hazard contexts [11,12,13]. However, comparative analyses linking different hazard types to structural responses within the same network remain limited.

Beyond the context of individual hazards, recent work has emphasized the importance of integrating structural and multi-hazard perspectives in the analysis of transport network vulnerability. Research on transportation resilience has highlighted that network response to disruption is strongly influenced by underlying topology, interdependencies, and the nature of perturbation mechanisms rather than hazard exposure alone [2,11,14]. These studies suggest a shift from purely performance-based assessments towards more structure-aware interpretations of vulnerability, exclusively in complex and spatially heterogeneous networks.

Despite the increasing literature on transport network vulnerability and resilience, a major challenge persists in the conceptualization and interpretation of vulnerability. A significant number of studies take an implicit view of vulnerability as something that is externally caused by hazard exposure. As a result, these studies employ analytical approaches that focus on the magnitude of disruption rather than the structure of response. Such an interpretation, however, might mask a significant difference between the point of disruption and the response of the network to disruption. In structurally heterogeneous networks, the same amount of disruption can lead to widely varying results, depending on the role that disrupted components play in the network. This finding indicates that vulnerability is not solely a property of the intensity of the hazard; rather, it is an emergent property of hazard characteristics and network structure. It is therefore necessary to adopt a structure-aware perspective to understand the propagation of disruption throughout the network and to comprehend why some failures cause localized disruption, while others cause system-wide disruption.

Central Java Province, Indonesia, is not the primary subject of analysis in this study; rather, it serves as a representative testbed. The area is characterized by the presence of lowland flood prone zones and mountainous landslide prone zones. Furthermore, the main road network functions as a significant regional backbone. The introduction of new toll roads has resulted in increased structural complexity in terms of enhanced long-distance connectivity. The implementation of such infrastructure has the potential to enhance the overall performance of the network. Nevertheless, it may also lead to alterations to the redundancy structure of the network, thereby increasing its reliance on a particular corridor, as observed in studies conducted on hierarchical transport networks and infrastructure expansion [4,15]. This prompts the fundamental question of whether increased connectivity results in greater structure during the periods of disruption.

The objective of this study is to answer this question by developing a graph-based framework to measure the degradation of connectivity in the primary road network of Central Java as a result of the disruption. The network is modeled as an undirected graph with weighted edges, as is frequently employed in transport network analysis [4,16] where the nodes represent intersections and the edges correspond to road segments with weights proportional to their length. The

spatial overlay technique is employed to identify hazard-exposed segments, which are then systematically removed under several scenarios. A comparison of network conditions with and without toll road integration is made using the largest connected component, the average shortest path length and network efficiency [17,18].

The novelty of this study is that it considers connectivity degradation as a structure-conditioned response to hazard-induced perturbations. In particular, the study: (i) reveals disruption signatures specific to each hazard between flood and landslide scenarios; (ii) explores the effects of toll road integration on structural vulnerability under disruption; and (iii) demonstrates that higher baseline connectivity does not necessarily lead to higher robustness. This study thus contributes to the field of graph-based road network analysis by moving it beyond a descriptive disruption assessment to an interpretation of vulnerability based on the structure of the network.

2. Materials and Methods

2.1. Study context and network representation scope

The objective of this study is to explore the concept of structure-conditioned vulnerability in road network, with the primary road network of Central Java Province, Indonesia serving as an empirical testbed (Fig. 1). The reason for selecting Central Java is based on a consideration that it has been documented as having a history of frequent flood and landslide events, which has been identified in national disaster assessments [19,20]. These hazards occur in both lowland and mountainous areas, and hazard frequency is high, combined with high geomorphological contrast. This renders the area especially well suited to the study of the various types of disruption and their exposure of underlying structural vulnerability.



Fig. 1. Map of the study area, demonstrating the primary road network and geomorphological setting of Central Java Province

Instead of the case being the focus of the investigation, the analysis employs this network to demonstrate how connectivity loss under disruption is determined by underlying topology. The primary road network has been selected as it constitutes the fundamental infrastructure for interregional connectivity,

encompassing national arterial roads, primary collectors and provincial primary roads. To maintain a network-scale perspective and to focus on structural connectivity, lower-order urban roads are excluded.

The spatial road network data was obtained from official sources, namely the Ministry of Public Works and Housing (MoPWH) and the Central Java Provincial Government that contained the geometric and functional attributes of the road network. Toll road corridors, which have grown significantly in recent years, are integrated as structural modifiers to evaluate their impact on connectivity both in baseline and disrupted scenarios. The primary road network and geomorphological setting of Central Java Province are illustrated in Fig. 1.

2.2. Graph representation and network modelling

The road network is represented as an undirected graph G as defined in Eq. (1):

$$G = (V, E) \tag{1}$$

where V is the set of nodes and E is the set of edges. This representation is adopted not merely as a computational model, but as a structural abstraction that captures the topological relationships governing connectivity within the network. The system is analyzed by breaking it down into nodes and edges, thus enabling the impact of network structure to be analyzed separately from operational factors such as traffic volumes, traffic directions, and capacity limits. This abstraction facilitates the identification of the influence of structural dependences on disruption vulnerability.

A multi-stage preprocessing procedure was employed to ensure that the graph represents functional connectivity. The process of converting the raw geometric representation to a structurally meaningful graph is depicted in Fig. 2. As demonstrated in Fig. 2, in the initial network representation, there are numerous intermediate nodes that are introduced due to geometric segmentation. Nevertheless, these intermediate nodes are not utilized for functional connectivity. The

elimination of these redundant nodes is achieved by means of algorithmic simplification, thereby maintaining the continuity of road segments. The implementation of topological correction ensures that the node–edge relationships are accurate in terms of real intersections and connectivity. The resulting graph is a structurally coherent network where nodes are meaningful junctions and links between nodes are functional. This process is critical to ensure that structural connectivity is represented in subsequent disruption analysis and not artefacts of the original geometric representation.

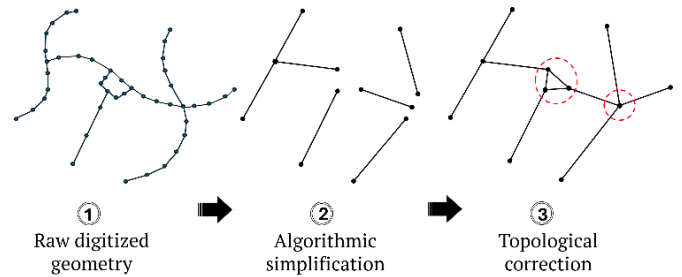


Fig. 2. Demonstration of geometry simplification steps after row-digitized data: algorithmic simplification followed by topological correction

The network utilized for analysis is presented in Fig. 3. The simplified and topologically corrected graph represents the main road network as a coherent structural system as illustrated in Fig. 3. The nodes correspond to significant road junctions and intersections, with the edges representing the functional road sections of the network between the nodes. The incorporation of toll road corridors (illustrated in red) enables the consideration of the network not only as a fixed structure, but also as a network that can be structurally modified. This representation is utilized for the subsequent disruption analysis, in which the loss of connectivity is determined as a function of network topology. The analysis emphasizes the significance of structural connectivity in comparison to mere geographic detail.

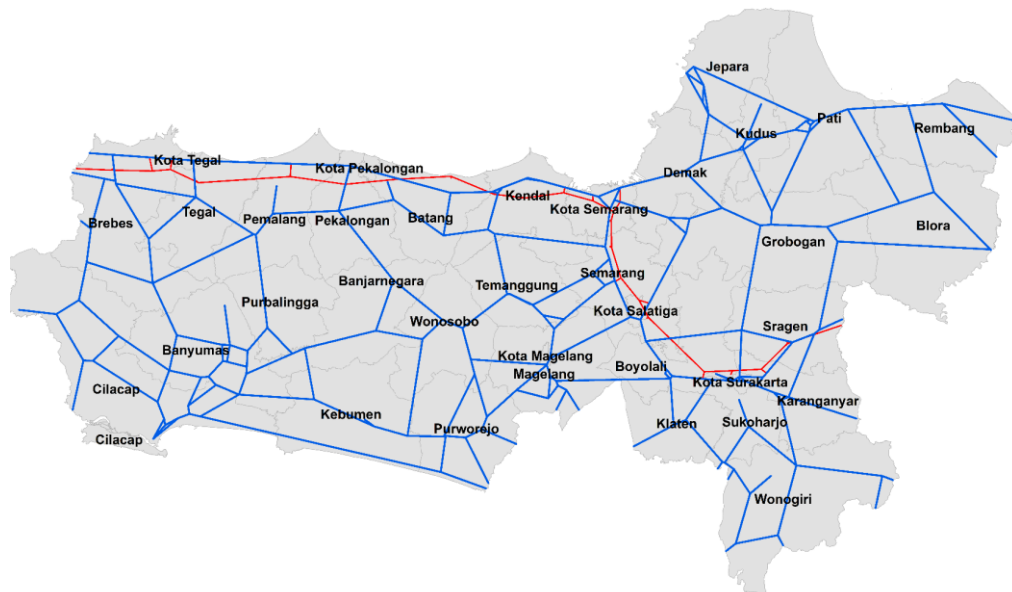


Fig. 3. Simplified and topologically corrected graph representation of the primary road network in Central Java, with toll road corridors highlighted in red

2.3. Hazard attribution as structural perturbation

The acquisition of flood and landslide hazard data was conducted through the InaRISK platform from the National Disaster Management Agency (BNPB). These data sets are organized into tiers of hazard exposure categorized as low, medium or high through a combined evaluation of environmental and historical conditions. In this framework, hazards are treated as external perturbations applied to the network, rather than as direct determinants of vulnerability. Hazard information is spatially attributed to network edges by identifying intersections between road segments and hazard zones.

The disruption is then simulated by means of selective removal of hazard-exposed edges. This removal is interpreted

as a structural failure mechanism, enabling the analysis to reveal how connectivity loss emerges from the underlying topology of the network. The baseline graph remains unchanged prior to disruption, thereby ensuring that vulnerability is evaluated as an intrinsic property of the network rather than as a function of hazard representation.

Fig. 4 and 5 illustrate the spatial distribution of flood and landslide hazards in the study area, respectively. The pervasiveness of flood hazard exposure is illustrated by extensive spatial patterns that are potentially impactful on large parts of the network, as illustrated in Fig. 4.

In contrast, Fig. 5 indicates that landslide hazards are more spatially concentrated, with disruptions tending to be localised but structurally critical, mostly in mountainous and hilly regions. These contrasting spatial characteristics can be used as

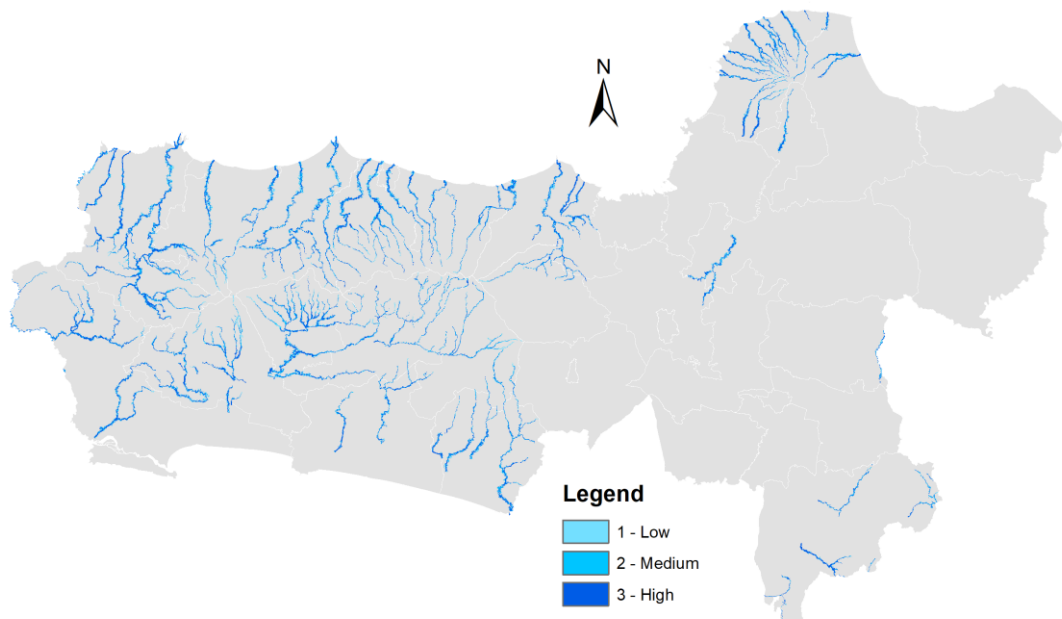


Fig. 4. Flood hazard exposure in Central Java Province, shown in three hazard severity levels according to BNPB

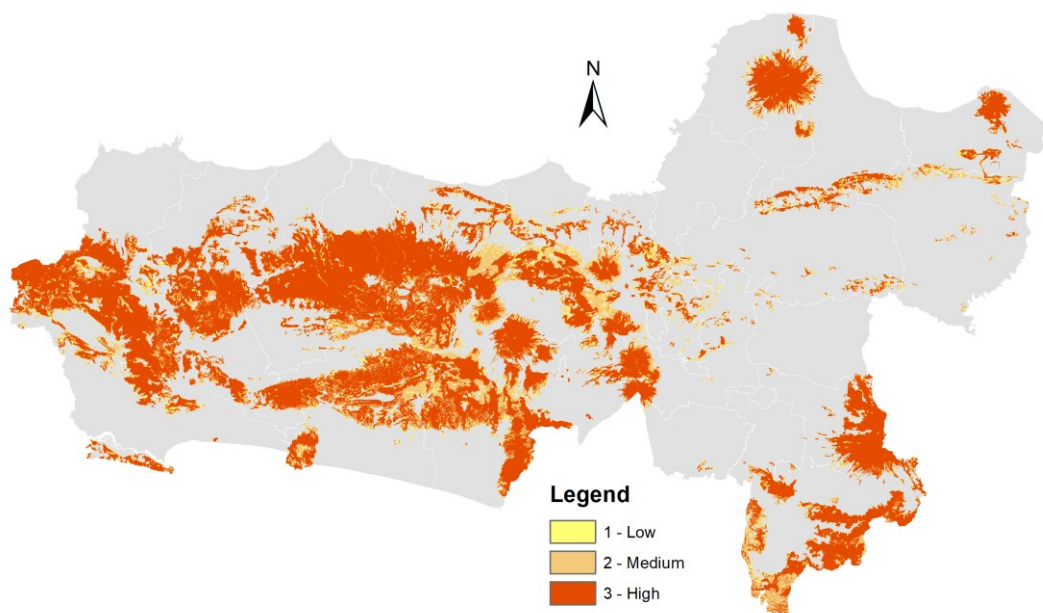


Fig. 5. Landslide hazard exposure in Central Java Province, shown in three hazard severity levels according to BNPB

a basis for understanding hazard-driven disruptions as different modes of structural perturbations on the network, not just in terms of the extent of exposure. This distinction is imperative to the understanding of the different aspects of underlying network vulnerability that are manifested by the different types of hazards.

2.4. Network disruption scenarios

A set of disruption scenarios is constructed to systematically probe how different forms of perturbation reveal structural responses within the network. Rather than serving solely as simulations of hazard conditions, these scenarios are designed to examine how connectivity loss emerges from the underlying topology under varying disruption mechanisms, magnitudes, and spatial configurations.

The disruption scenarios in this study are summarized in Table 1. The scenarios are divided into three categories: hazard-type, severity-based, and spatially localized disruptions, as illustrated in Table 1. Each group corresponds to a distinct method of perturbing the network structure.

Hazard-type scenarios are utilized to simulate the effects of the various disruption mechanisms by modelling the failure of the hazard in isolation. This enables the analysis to separate the effects of different hazard processes on the network structure, which yield different connectivity degradation patterns.

Severity-based scenarios involve the progressive structural degradation of road segments by means of incremental removal, with the aim of exposing those segments to increasing levels of hazard. This formulation facilitates the observation of the evolution of connectivity in response to increasing perturbation, thereby enabling the determination of whether the network fragmentation occurs slowly or suddenly as a function of the structural properties of the network.

Spatially localized scenarios focus on the impact of where the disruption occurs by targeting edge removal in specific areas and administrative units. In this application, Central Java is segmented into three broad zones: northern, central, and southern zones, which are based on the geomorphological conditions and spatial aggregation of hazard exposure. Other regency level scenarios are applied where a high number of

exposed road segments are present. These configurations enable the analysis to examine the effect of the spatial location of disruptions on connectivity loss, irrespective of the number of edges affected.

All analyses are performed for both baseline network configurations: with and without toll road integration, in addition to these groups of scenarios. The employment of this dual representation facilitates the analysis of the impact of the structural changes, which are represented by the addition of major infrastructure, on the network vulnerability under various perturbation scenarios. When considered as a whole, these scenarios offer a structured approach to identify vulnerabilities in various aspects of disruption, ranging from mechanism, intensity, to spatial distribution, at the level of the network.

2.5. Structural connectivity indicators

The evaluation of network performance in the presence of disruption is undertaken by employing graph-theoretic indicators that prioritize structural connectivity over operational performance. The indicators have been selected to represent complementary aspects of network integrity, accessibility, and efficiency, thereby enabling the analysis to focus on how disruption affects the underlying topology of the network.

The largest connected component (LCC) is employed to represent network integrity, indicating the extent to which the network remains structurally intact under disruption. The LCC is defined as the maximum number of nodes that remain mutually reachable. Let $C_k \subseteq V$ be a connected component containing node k in a disrupted graph G_d . The largest connected component is defined as in Eq. (2):

$$LCC(G_d) = \max_k |C_k| \quad (2)$$

A reduction in LCC value indicates network fragmentation, signifying that smaller proportion of the network remains internally connected. For comparative purposes across scenarios, the LCC value is standardized relative to the total number of nodes in the baseline graph as delineated in Eq. (3):

Table 1. Disruption scenarios designed to probe structural connectivity responses under hazard-induced perturbations

Scenario Group	Scenario Description	Hazard Type	Disruption Basis	Network Treatment
S1	Hazard-type disruption	Flood	Removal of road segments intersecting flood hazard zones	Edges removed based on hazard type
S2	Hazard-type disruption	Landslide	Removal of road segments intersecting landslide hazard zones	Edges removed based on hazard type
S3	Severity-based disruption	Flood	Progressive removal of segments exposed to increasing flood hazard levels	Stepwise edge removal
S4	Severity-based disruption	Landslide	Progressive removal of segments exposed to increasing landslide hazard levels	Stepwise edge removal
S5	Spatially localized disruption	Flood	Removal of exposed segments within selected regions (zone-based) and administrative units (regencies)	Spatially constrained edge removal
S6	Spatially localized disruption	Landslide	Removal of exposed segments within selected regions (zone-based) and administrative units (regencies)	Spatially constrained edge removal
S7	Baseline comparison	–	No disruption applied	Full network retained
S8	Toll road exclusion	–	Removal of toll road edges	Network without toll roads

$$LCC_r(G_d) = \frac{LCC(G_d)}{n} \quad (3)$$

The evaluation of accessibility within the network is conducted through the utilization of the average shortest path length (ASPL), which measures the efficiency of travel between nodes within the largest connected component. Let d_{ij} denote the shortest path distance between nodes i and j , and let C_{LCC} be the number of nodes in the largest connected component, the ASPL is computed as in Eq. (4):

$$ASPL(G_d) = \frac{1}{|C_{LCC}|(|C_{LCC}| - 1)} \sum_{i \neq j \in C_{LCC}} d_{ij} \quad (4)$$

An increase in ASPL indicates reduced accessibility, as paths between nodes become longer due to disruption.

The third indicator is network efficiency, which measures the overall effectiveness of connectivity by considering the inverse of shortest path distances. For each pair of nodes i and j , the shortest-path distance is d_{ij} , and the corresponding efficiency ε_{ij} is defined as in Eq. (5):

$$\varepsilon_{ij} = \begin{cases} \frac{1}{d_{ij}}, & \text{if } i \neq j \text{ and connected} \\ 0, & \text{if not connected} \end{cases} \quad (5)$$

Following the formulation by Latora and Marchiori [17], the overall efficiency of the disrupted network $E(G_d)$ is determined by calculating as the average efficiency across all node pairs, as formulated in Eq. (6):

$$E(G_d) = \frac{1}{n(n-1)} \sum_{i \neq j} \varepsilon_{ij} \quad (6)$$

To facilitate comparison across scenarios, efficiency values are normalized against the baseline network G_0 , yielding Eq. (7):

$$E_r(G_d) = \frac{E(G_d)}{E(G_0)} \quad (7)$$

A decrease in normalized efficiency E_r indicates the increased difficulty of movement between nodes due to disruption.

Collectively, these indicators provide complementary perspectives on structural connectivity loss, capturing not only the extent of network fragmentation, but also its implications for accessibility and overall connectivity efficiency. By focusing on these structural measures, the analysis isolates the topological dimensions of vulnerability independent of traffic flow dynamics. All indicators are evaluated relative to baseline conditions to quantify the extent of connectivity degradation under each disruption scenario.

2.6. Computational framework

A structured computational framework is employed to evaluate the amount of connectivity loss of the structure when it is perturbed in a controlled manner. Subsequently, the basic network configurations with and without integration of toll road are constructed and evaluated using a selection of

designated connectivity indicators. The baseline conditions are employed as a reference state for the disruption scenarios.

Subsequently, hazard exposed edges are selectively removed to produce disrupted network states, based on the defined scenarios. In this study, the set of nodes is kept constant, thereby ensuring that any observed changes in performance are attributable to the degradation of connectivity, rather than the changes in network size. It is therefore possible to distinguish between the impact of disruption on the integrity and accessibility of the network from that of structure. Subsequent to the implementation of the disruption, the connectivity indicators are computed for the various scenarios and then compared with the baseline indicators. The process of comparative assessment facilitates the quantification of the performance degradation in the different modes of perturbations. These modes may include different types, severity, and spatial localization of hazards. This framework overall offers a controlled environment for studying the emergence of connectivity loss in a network under disruption due to its topology. The systematic application of perturbations, coupled with the analysis of their structural implications, has the potential to facilitate an understanding of vulnerability. This understanding suggests that vulnerability should be regarded as not only as a direct function of the hazard, but also as an intrinsic feature of the network

3. Results

3.1. Baseline network characteristics

The baseline connectivity of the primary road network is evaluated under two structural configurations: without and with toll road integration. The corresponding connectivity indicators are summarized in Table 2.

Table 2. Connectivity performance of the baseline graphs as primary road network representations

Indicators	Without-Toll	With-Toll
LCC	1	1
ASPL (km)	145.65	138.08
Global Efficiency	0.000069	0.000052

As demonstrated in Table 2, both configurations exhibit a largest connected component (LCC) value of 1, indicating that the network maintains full connectivity under the baseline conditions. This guarantees that prior to any disruption, the network is one connected system where all nodes can reach each other, including in the event of toll road infrastructure.

The differences between the two configurations are primarily manifested in the indicators related to accessibility. The addition of toll roads result in a decrease of the average shortest path length (ASPL) from 145.65 km to 138.08 km, thereby indicating a better long-range accessibility within the network. Nevertheless, a marginal decline in global efficiency has been observed. This decline is related to the increase in the number of nodes and edges in the network structure, and this can impact the normalization of efficiency measures.

The findings of this study demonstrate a significant distinction between structural integrity and accessibility

performance. The topological coherence of the networks is completely preserved in both configurations, although toll roads improve connectivity in terms of travel efficiency.

It is important to note that Table 2 serves as a reference condition to understand the connectivity degradation during further disruption scenarios. While both configurations may appear structurally similar at rest, their reactions to perturbation could vary based on the interaction between the added infrastructure and the underlying topology. The baseline analysis thus serves as the basis for the analysis of connectivity loss when the network is subjected to hazard-induced disruptions.

3.2. Hazard-specific disruption results

Disruption scenarios based on hazard type reveal distinct patterns of connectivity degradation between flood- and landslide-induced perturbations. The corresponding changes in connectivity indicators for both network configurations are summarized in Table 3. As demonstrated in Table 3, there is a consistent moderate loss of connectivity due to flood-induced disruption in all indicators. The largest connected component (LCC) undergoes a gradual decrease, suggesting that there is partial fragmentation of the network, but a relatively large, connected subgraph persists. The average shortest path length (ASPL) exhibits a decrease at a moderate rate, while global efficiency demonstrates a decrease in a smooth yet not sharp manner, indicating a deterioration in accessibility. These patterns indicate that flood exposure is likely to impact many segments of the network, resulting in a diffuse connectivity degradation.

Conversely, the behavior of the landslide-induced disruption is quite different. As demonstrated in Table 3, the LCC exhibits a substantial decline even at similar exposure levels, indicating that the network is rapidly disintegrating into smaller disconnected components. This phenomenon is concomitant with a significant increase in ASPL and a significant decrease in global efficiency, indicating significant loss of accessibility

and loss of network cohesion. The effect of landslides is not widespread but rather concentrated in specific segments, which are crucial for maintaining connectivity, contradicting to the effects of floods.

Table 3. Performance comparison of hazard-specific disruption scenarios for flood and landslide across without-toll and with-toll configurations

Model	Edges removed	Com-ponents	LCC Size	ASPL (km)	Global Efficiency
Baseline (Without toll)	–	1	205	145.65	0.000069
Flood (Without toll)	88	52	108	102.43	0.000021
Landslide (Without toll)	94	59	46	72.98	0.000033
Baseline (With Toll)	–	1	250	138.08	0.000052
Flood (With Toll-Affected)	107	64	132	89.18	0.000023
Flood (With Toll-Intact)	104	61	132	89.18	0.000023
Landslide (With Toll-Affected)	105	62	57	71.25	0.000035
Landslide (With Toll-Intact)	103	60	63	69.99	0.000034

From these contrasting behaviors, two different disruption signatures are identified. The phenomenon of distributed and progressive degradation of connectivity is characterized by the deterioration in performance occurred in a distributed manner in view of the disruption caused by the flooding. By contrast,

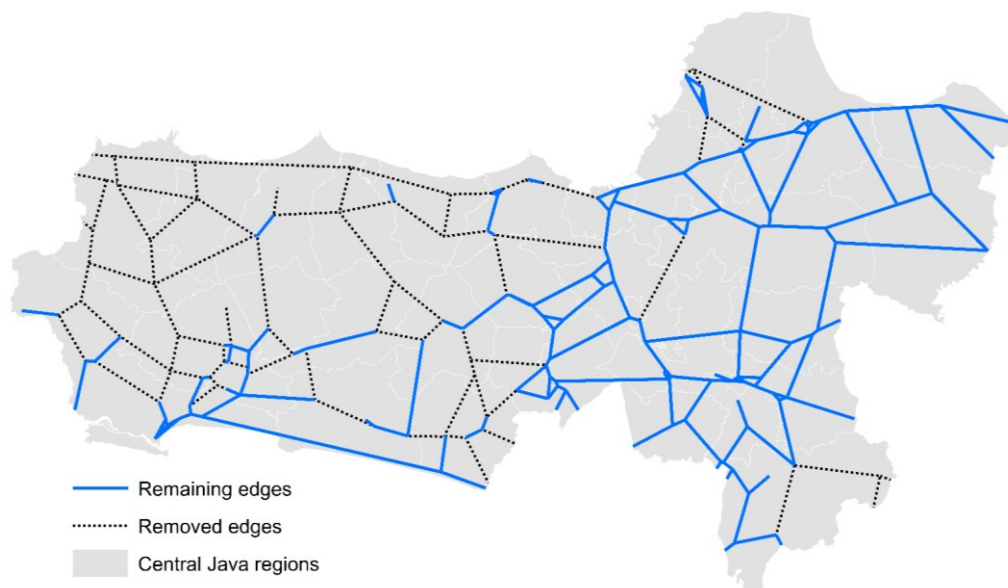


Fig. 6. Structural disruption pattern under a representative flood scenario, showing the spatial distribution of remaining and removed edges. This pattern reflects a distributed mode of structural perturbation

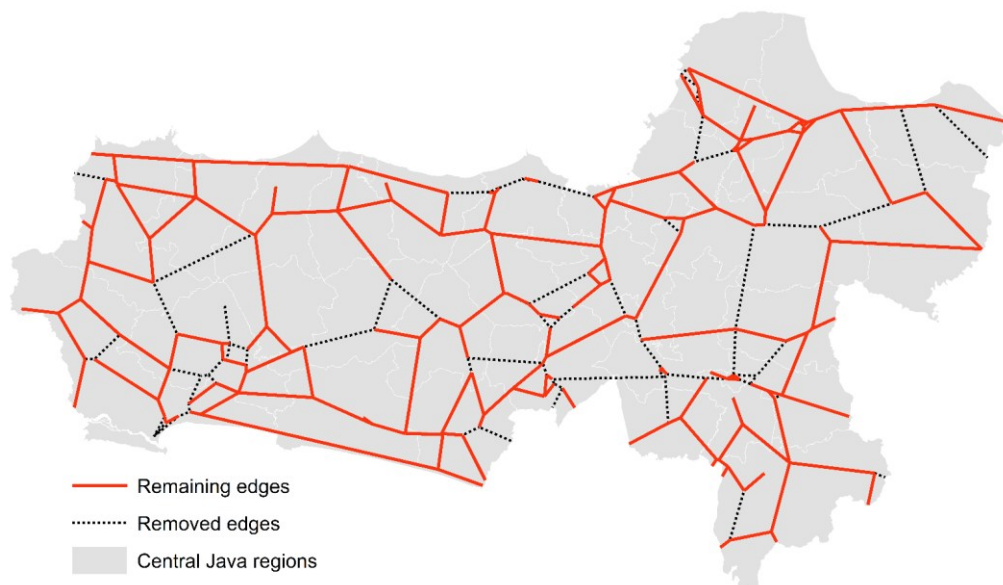


Fig. 7. Structural disruption pattern under a representative landslide scenario, showing the spatial distribution of remaining and removed edges. This pattern reflects a localized and structurally critical mode of perturbation

the disruption caused by a landslide is localized, yet structurally important, with the loss of critical edges resulting in disproportionate connectivity loss.

This difference is further demonstrated in Fig. 6 and 7, which depict the spatial distribution of the remaining and removed edges in representative flood and landslide scenarios, respectively. The flood scenario demonstrates a general disruption of the network throughout, with relatively small differences between the various edges (Fig. 6). Conversely, the landslide scenario manifests a localized removal of edges, resulting in the fragmentation of topologically sensitive areas of the network becoming fragmented into isolated clusters (Fig. 7). A comparison of network configurations with and without toll roads shows that these disruption signatures are not fundamentally changed by structural changes. While the introduction of toll roads can enhance the basic accessibility, it does not preclude the development of fragmentation in landslide conditions and the spread of degradation in flood conditions.

The findings suggest that the loss of connectivity is not only dependent upon the extent of hazard exposure, but also on the interaction between the disruption and the topology of the network. In this context, hazard scenarios are perturbation mechanisms that expose various facets of structural vulnerability in the network.

3.3. Severity-based disruption results

It is evident that the severity-based disruption scenarios provide a more comprehensive understanding of the extent of connectivity reduction with increasing disruption severity. The network does not respond in a consistent manner; rather, it exhibits different degradation pathways for each hazard, as seen in the tabulated results (Tables 4 and 5) and the respective connectivity curves (Fig. 8 and 9).

As demonstrated in Table 4 and the corresponding trends in Fig. 8, there has been a gradual and continuous degradation of

connectivity due to flood induced disruption. As more severe levels of severity are taken into account, the LCC becomes smaller, meaning that the network is increasingly fragmented. The same applies to the average shortest path length (ASPL), which gradually grows, and to the global efficiency, which decreases in a regular fashion. As demonstrated in Fig. 8, the steepest gradients occur between low and moderate severity, with the rate of degradation slowing down as severity increases, resulting in a curve, which increasingly flattens off. This behavior indicates that the disruption caused by flooding impacts many sections of the network, and the connectivity loss is distributed rather than catastrophic.

Table 4. Performance comparison of severity-specific disruption scenarios for flood across without-toll and with-toll configurations

Severity Level*	Network Model	Edges Removed	LCC Size	ASPL (km)	Global Efficiency
L	Without Toll	58	155	165.99	0.000113
L	With Toll	70	179	149.76	0.000090
L+M	Without Toll	83	113	103.38	0.000020
L+M	With Toll	98	137	90.55	0.000022
L+M+H	Without Toll	88	108	102.43	0.000021
L+M+H	With Toll	107	132	89.18	0.000023

*L: low; M: medium; H: high

Conversely, the landslide scenarios, as illustrated in Table 5 and Fig. 9, indicate a highly different trend. There is little change in the LCC across the level of severity, suggesting that the main structural fragmentation occur at the early stages of disruption. In contrast, ASPL increases rapidly as the level of disruption increases and stabilizes, indicating that the most severe loss of accessibility occurs during the first order of disruption. This leads to a typical pattern of quick change and saturation, as further increases in severity have smaller effects

on the connectivity indicators (see Fig. 9). This behavior indicates that the disruption of the connectivity induced by the landslides is controlled, that is, the loss of a few structurally critical edges appears to cause a connectivity loss that is disproportionate.

As illustrated in Table 4 and 5, as well as in Fig. 8 and 9, two different degradation pathways are evident. The phenomenon of disruption to connectivity due to flooding can be conceptualized as unfolding in a progressive manner. As the perturbation levels increase, the connectivity decreases. By contrast, the disruption caused by landslides demonstrates an early-stage structural collapse and saturation, indicating the sensitivity of the network to local failures of critical connections.

Table 5. Performance comparison of severity-specific disruption scenarios for landslide across without-toll and with-toll configurations

Severity Level	Network Model	Edges Removed	LCC Size	ASPL (km)	Global Efficiency
L	Without Toll	85	46	69.00	0.000033
L	With Toll	95	57	68.68	0.000035
L+M	Without Toll	94	46	72.98	0.000033
L+M	With Toll	105	57	71.25	0.000035
L+M+H	Without Toll	94	46	72.98	0.000033
L+M+H	With Toll	105	57	71.25	0.000035

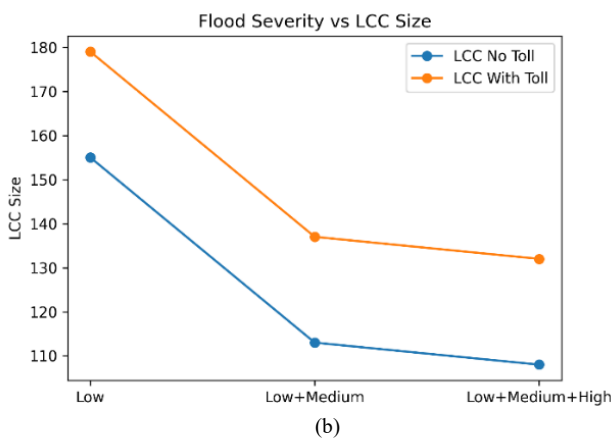
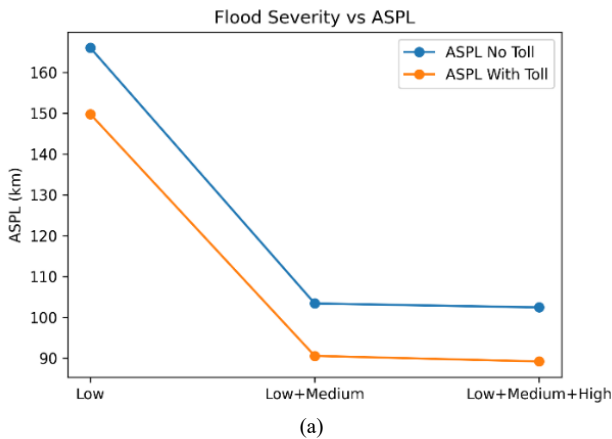


Fig. 8. Connectivity degradation trajectories under increasing flood severity levels, showing changes in (a) average shortest path length (ASPL) and (b) largest connected component (LCC). The curves illustrate a non-linear, progressively saturating pattern of degradation, characteristic of distributed disruption

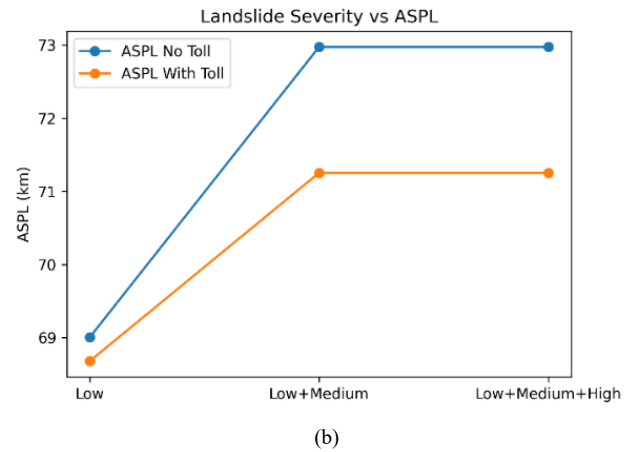
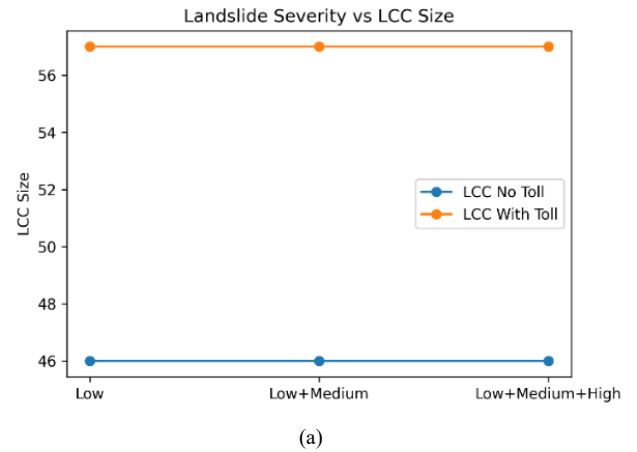


Fig. 9. Connectivity degradation trajectories under increasing landslide severity levels, showing changes in (a) largest connected component (LCC) and (b) average shortest path length (ASPL)

The findings suggest that the relationship between hazard severity and connectivity loss is intrinsically non-linear and highly dependent upon network topology. The effects of floods are distributed along numerous segments, whereas landslides affect specific structural elements, resulting in different manifestations of vulnerabilities. The comparison between network configurations with and without toll roads also indicates that structural changes can affect the degradation rate under distributed perturbations but are not very effective if the perturbations are applied to topologically important edges.

3.4. Spatially localized disruption results

More insight into the impact of the perturbation location on connectivity loss is afforded by spatially localized disruption scenarios. Spatial scenarios emphasize the structural significance of the location of disruptions in the network, as opposed to severity-based analysis, where the focus is on the intensity of the disruption. As demonstrated in the results summarized in Table 6, the connectivity degradation exhibits significant variation in different regional zones even for similar number of removed edges. For instance, for an event in the northern zone, a disruption from flooding can lead to a loss of up to 4.4–6.0% in LCC, while in central and southern zones, the loss can be as low as 1.0–1.2% in LCC. A similar trend is observed for accessibility, characterized by a reduction in

Table 6. Connectivity performance under spatially localized disruption scenarios across three regional zones of Central Java Province

Hazard Type	Model	Zone	Edges Removed	Baseline LCC	Disrupted LCC	% Reduction LCC	Baseline ASPL (km)	Disrupted ASPL (km)	Δ ASPL (km)	Efficiency Change
Flood	Without-Toll	North	38	205	196	-4.4%	145.65	141.49	-4.16	+8.7%
Flood	Without-Toll	Central	47	205	203	-1.0%	145.65	148.01	+2.36	+0.8%
Flood	Without-Toll	South	50	205	203	-1.0%	145.65	148.01	+2.36	+0.8%
Flood	With-Toll	North	46	250	235	-6.0%	138.08	132.33	-5.75	+9.6%
Flood	With-Toll	Central	59	250	247	-1.2%	138.08	137.96	-0.12	+1.9%
Flood	With-Toll	South	51	250	235	-6.0%	138.08	132.33	-5.75	+9.6%
Landslide	Without-Toll	North	30	205	202	-1.5%	145.65	145.07	-0.58	+2.4%
Landslide	Without-Toll	Central	52	205	203	-1.0%	145.65	148.01	+2.36	+0.8%
Landslide	Without-Toll	South	70	205	203	-1.0%	145.65	148.01	+2.36	+0.8%
Landslide	With-Toll	North	35	250	247	-1.2%	138.08	137.96	-0.12	+1.9%
Landslide	With-Toll	Central	60	250	247	-1.2%	138.08	137.96	-0.12	+1.9%
Landslide	With-Toll	South	70	250	247	-1.2%	138.08	137.96	-0.12	+1.9%

ASPL in the northern zone and an increase in other regions, suggesting different accessibility responses.

The spatial positioning of disrupted edges is more significant than the number of disrupted segments, as demonstrated in this pattern. The phenomenon of loss of connectivity, therefore, cannot be attributed solely to disruption; its interaction with other structurally significant components of the network is also a contributing factor. Specifically, disturbances in areas that are connectivity bridges between major sub-networks have disproportionately large effects on network integrity. These findings serve to reinforce the interpretation that network vulnerability is inherently structure conditioned. The spatial heterogeneity of disruption impacts is a result of the underlying differences in topological importance across regions; some regions have edges that are more critical to the overall connectivity.

In general, the spatial scenarios demonstrate that the impact of connectivity loss is highly sensitive to the location of the loss, thereby reinforcing the notion of hazards as perturbation mechanisms that expose underlying structural relationships in the network, rather than as uniform sources of damage.

3.5. Toll road influence on connectivity performance

The present study investigates the influence of toll road integration on network connectivity, examining this influence across baseline and disruption scenarios to assess its role as a structural modifier. The findings of this study suggest that, in contrast to the hypothesis that network robustness is enhanced through consistent improvement, the effect of toll roads varies dependent on the nature of the perturbation applied to the network. As demonstrated in Table 2, the ASPL is shown to decrease from 145.65 km to 138.08 km when toll roads are included under the baseline conditions. This indicates that accessibility is increased. However, this improvement does not result in a change in the network's structure, as both components remain fully interconnected. Toll roads are characterized by the high level of complexity in the disruption scenarios. The integration of toll roads has been demonstrated to have a small difference in connectivity performance in flood-induced scenarios. For instance, the decrease of LCC is slightly

less pronounced and the increase in ASPL is less significant compared to the without-toll configuration (see Table 3). This finding indicates that the additional links provided by the toll roads provide extra redundancy in the presence of when perturbations.

Conversely, in the landslide disruption scenario, the toll roads are unable to maintain connectivity. As seen in Tables 3 and 5, the LCC reductions remain significant, and the ASPL exhibits a significant increase even with toll integration, indicating that the network remains highly sensitive to the removal of structurally critical edges. This finding suggests that the addition of infrastructure does not fundamentally alter the network's vulnerability to localized disruption.

Taken as a whole, these results highlight a fundamental distinction between efficiency enhancement and structural robustness. The integration of toll roads has been demonstrated to enhance accessibility during both normal and slowly deteriorating situations. Nevertheless, in the event of disruption to key connectivity corridors, the efficacy of this integration is reduced. In this way, toll roads can be regarded as a tool for enhancing network efficiency, rather than a measure for protecting network integrity against fragmentation.

The findings, in terms of the type of hazard, its severity, spatial distribution and network configuration, indicate that disruption mechanisms and underlying network topology interact to regulate connectivity degradation. The network does not react in the same way to the exposure to hazards; rather, it exhibits different patterns of vulnerabilities depending on the interplay between perturbations and structurally significant elements. These findings establish a coherent basis for interpreting network vulnerability as an intrinsic structural property, which is further examined in the following discussion.

4. Discussion

The results indicate that the degree of connectivity loss in the road network of Central Java cannot be solely understood by the magnitude of disruption. Instead, it is determined by more fundamental interaction between disruptions and the underlying network structure across multiple dimensions of

disruption. This finding is consistent with the emerging research on network science and transport resilience, which emphasizes that vulnerability is highly dependent not only on exposure to hazards, but also on the topological structure of a network [1,3,18]. Recent studies have also demonstrated that structural properties can influence the response of the system when it is disrupted, especially in complex and spatially heterogeneous transport networks [13,21]. In this sense, the vulnerability of a network is an inherent characteristic of the network topology and is exposed, not created, by hazard-related perturbations. This finding implies a conceptual change from hazard-based to structure-based vulnerability of the network.

One of the key findings of this study is the concept of hazard-specific disruption signatures. Flood-induced disruptions are of a distributed failure type, resulting in a gradual degradation of network performance. This finding is consistent with the findings of recent research on the subject of large-scale flood impacts, which suggests that disruption is likely to be spatially widespread, and that some of the impact can be offset by alternative routing [7,8,9]. In contrast, landslide-induced disruptions exhibit a localized yet structurally consequential pattern, characterized by rapid fragmentation and abrupt connectivity collapse. This phenomenon is similar to what has been observed in recent studies of targeted disruptions and critical infrastructure failure, where local damage to pivotal links can have disproportionate impacts on the system level [11,13]. In network theory, these links can be conceptualized as articulation edges, whose removal results in the division of the network into distinct components. In this regard, it is important to remember that hazards do not create vulnerability, they expose it. This phenomenon is further reflected in Fig. 6 and 7, demonstrating that spatially extensive flood disruptions result in a gradual degradation, whereas spatially limited landslide disruptions lead to disproportionate fragmentation when they intersect with structurally critical links. These patterns are directly related to the different degradation trajectories in the results, with the gradual loss of connectivity during flood-induced disruption and the structural collapse of the early degradation stage during landslide-induced disruption. This separation corresponds to transport network studies, which have suggested that transport disruptions of floods are generally distributed in space and can be partially buffered by alternative paths [7] and [11]. Localized disruptions such as landslides are likely to have disproportionate impacts on the system level if they affect structurally significant links [22] and [23].

This separation of the distributed and localized disruption mechanisms provides a more clear-cut structural interpretation of network vulnerability. Distributed disruptions result in progressive degradation, which can be absorbed by redundant pathways in the network. Conversely, localized disruptions have the potential to induce disproportionate connectivity loss if they affect topologically critical links that function as bridges between major sub-networks. As with the spatial and severity-based scenarios, the impact of the equivalent disruption can vary significantly based on the location of the disrupted edges in the network. This observation serves to further emphasize the importance of spatial configuration: Vulnerability is not evenly distributed throughout the network; rather, it is localized

in structurally sensitive areas whose disruption controls the performance of the network. This finding is in line with the principles of network science, which has demonstrated that the contribution of individual components to the network topology can significantly impact the system's response. Research on infrastructure networks has demonstrated that failures on important links may have disproportionate impact on the size of the failure [23,24]. Disruptions along structurally important corridors have been observed to have similar effects on transport systems [22]. This interpretation is consistent with the recent advances in the field of complex network theory, which suggest that the effect of perturbations depends on the role of the impacted components in the network, rather than on their attributes alone [3,18,25,26].

In this context, the uniform distribution of vulnerability is not possible. Instead, a higher density of vulnerability occurs in structurally sensitive areas, the failure of which determines the response of the system. Consequently, the degradation of connectivity should be understood as a structure-dependent process, in which the impact of disruption is mediated by the topological role of the affected components rather than by the extent of exposure alone.

The analysis of toll road integration further reveals a structural paradox in infrastructure development. The addition of toll roads has been demonstrated to improve the connectivity in the network, as evidenced by the optimized efficiency and reduced average path length. Nevertheless, it does not guarantee an improvement in network robustness in the event of disruption. Recent studies on the impacts of transport network expansion and hierarchy have also indicated that the introduction of new high-capacity links can lead to increased reliance on key corridors and reduced network functional redundancy [4,15,24]. The findings of this study demonstrate that networks with toll integration have similar or even higher levels of fragmentation during disruption, indicating the presence of potential dependency on structure in addition to connectivity. This phenomenon is similar to the observation made in infrastructure network studies, where capacity expansion not only leads to an increase the network efficiency, but also increases the dependency on the network's structure. This, in turn, results in a reduction in redundancy, thereby affecting its response to disruption [1,17,23,25]. In this sense, the function of toll roads is not merely to reinforce the system, but rather to act as structural modifiers that reshape network hierarchy and vulnerability patterns. This finding confirms the results demonstrating the difference between improving efficiency and making the structure more robust.

Furthermore, an analysis of the data indicates that the average shortest path length also decreases in cases of severe disruption. This finding demonstrates the need for careful interpretation of the metrics to ascertain the reliability of the results. This pattern is not necessarily an increase in accessibility; rather, it suggests a sign of network shrinkage, where peripheral nodes are disconnected, and excluded from the largest connected component. This phenomenon has been explored in classic and recent network robustness studies wherein fragmentation results in artificially short path lengths in residual subnetworks [17,18,27]. This indicates the potential for misinterpretation of performance metrics if the network topology is not taken into account, emphasizing the importance

of understanding metrics in the context of the dynamic network topology. This finding further supports the need for structure-aware interpretation of performance indicators.

The findings of this study demonstrate that a mere consideration of hazard exposure or the magnitude of disruption is insufficient to understand the vulnerability of road network; instead, it is a reaction to the hazard that is conditioned by the network's topology. Across various hazard types, severity levels, and spatial configurations, there is a consistent correlation between connectivity degradation and underlying structural dependencies, revealing vulnerability as an intrinsic property rather than an externally imposed condition. This view is consistent with the findings of other studies in network science, which have demonstrated that network topology is crucial factor in determining the resilience of a system [3,18]. Furthermore, recent studies in the transport sector have indicated the significance of network structure in determining the impact of disruptions [10,22,27].

Despite the identification of several types of network disruption and vulnerability in previous research, these phenomena have predominantly been examined in isolation. The present study advances this body of knowledge by demonstrating that these apparently distinct patterns can be understood as manifestations of a unified structural mechanism governed by network topology. In this regard, the value of the model lies not in the identification of novel modes of disruption but rather in the structural interpretation that facilitates the comprehension of the recurrent nature of the patterns, whatever the type of hazard and configuration.

Specifically, the identification of hazard-specific disruption signatures, the characterization of non-linear degradation trajectories and the demonstration of strong spatial sensitivity, provide an integrated structure-aware understanding of vulnerability. By establishing a correlation between disruption patterns and their underlying structural mechanisms, the analysis moves beyond descriptive assessment toward an explanatory perspective on network vulnerability.

This approach about hazards as perturbation mechanisms that expose network vulnerability rather than defining the network itself, changes the focus of analysis from an exposure-based assessment to a structural diagnosis. This provides a more robust foundation for comprehending the loss of connectivity in complex road networks and suggests that risk mitigation measures should be concentrated on identifying and strengthening structurally important elements of the network, rather than on a blanket increase of infrastructure. This interpretation eventually implies that vulnerability is not a consequence of disruption to be measured, but rather a situation to be comprehended in advance.

This structure-oriented perspective is consistent with the general aim of understanding complex spatial systems through model-based analysis. Recent studies have demonstrated the efficacy of spatial representations to discover underlying processes and to enhance the interpretation of phenomena and infrastructure planning concerning hazards [28,29]. These developments continue to depict how analytical frameworks based on the spatial structure of a system can facilitate the understanding of system behavior that is not obvious from surface observations.

Nevertheless, there are some disadvantages to these

contributions. Analysis assumes that all hazard-exposed links are removed, which is worst-case scenario for structural failure. This is a probable overestimate of the fragmentation occurred in the real world where hazard exposure more frequently leads to reduced capacity or speed [25]. Moreover, static hazard representations do not account for temporal dynamics and evolving disruption processes, which have been increasingly identified as important in infrastructure resilience research [14] and [30]. The simplicity of these simplifications reflects the structural focus of this study, as well as important areas for future work, such as the incorporation of partial degradation models, dynamic hazard processes, and traffic-based performance measures to better link structural analysis with operational realism.

5. Conclusion

The present study demonstrates that road network vulnerability is fundamentally shaped by structural properties rather than by hazard exposure alone. The findings indicate the presence of different hazard-specific signatures, with distributed disruptions leading to a gradual degradation, while localized disruptions can cause disproportionate fragmentation if they occur at structurally critical links. These patterns, along with the observed non-linear degradation trajectories, and strong spatial sensitivity, suggest the necessity for a re-evaluation of vulnerability as a structure-conditioned response to disruption. The analysis further demonstrates that an enhancement of the baseline connectivity, for instance through toll road integration, does not automatically lead to an increase in robustness. Conversely, connectivity gains can create new structural vulnerabilities, which can further reconfigure existing vulnerabilities within the network. This underlines the necessity for considering infrastructure development in terms of both efficiency and structural resilience in the face of disturbance. This study represents a significant advancement in graph-based road network analysis from descriptive disruption assessment to an explanatory, structure-aware understanding of vulnerability. By linking disruption patterns to their underlying structural mechanisms, the findings provide a more robust basis for infrastructure planning and risk management, particularly in hazard-prone regions. In such regions, the identification and strengthening of structurally critical links may prove more effective than uniform network expansion. Ultimately, understanding network vulnerability requires shifting attention from external hazards to the structural logic that governs network behavior.

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