International Journal of Transport Development and Integration
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Structural Vulnerability of a Primary Road Network under Alternative Graph Representations: Assessing the Role of Toll Roads in Central Java, Indonesia

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Received: 01-12-2026 **Revised:** 05-11-2026 **Accepted:** 05-21-2026

Citation: B. Kushari, M. I. Ramli, B. Bakri, and A. Arsyad, “Structural vulnerability of a primary road network under alternative graph representations: Assessing the role of toll roads in Central Java, Indonesia,” *Int. J. Transp. Dev. Integr.*, vol. 10, no. 2, pp. 492–513, 2026. https://doi.org/10.56578/ijtdi100211.

Abstract: Transportation-network disruptions caused by floods, landslides, and corridor failures have highlighted the importance of understanding structural vulnerability as an intrinsic property of regional transportation systems. While graph-based approaches are widely used in transportation-network analysis, less attention has been directed toward how graph representation choices influence the interpretation of regional connectivity and vulnerability. This study examines the primary road network of Central Java Province, Indonesia, by comparing three graph representations: a raw digitization-based graph, an algorithmically simplified graph, and a topologically corrected simplified graph. For each representation, non-toll and with-toll configurations incorporating the Trans-Java Toll Road system are analyzed. Structural vulnerability and regional connectivity patterns are evaluated using weighted average shortest path length (ASPL), betweenness centrality (BC), articulation analysis, and largest connected component (LCC) analysis. The results demonstrate that graph representation strongly conditions the interpretation of transportation-network structure and vulnerability. Raw digitization-based graphs inherit excessive geometric segmentation that obscures large-scale corridor organization and distorts criticality patterns, whereas simplified and topologically corrected representations reveal more functionally interpretable transportation structures. Toll-road integration substantially improves regional accessibility and strengthens east–west continuity along the northern transportation corridor. However, several inland and interregional connectors remain structurally important due to physiographic constraints and inherited corridor dependency. The findings suggest that accessibility enhancement and structural robustness should not be interpreted as automatically equivalent within regional transportation networks. More broadly, the study highlights the importance of representation-aware approaches for interpreting structural vulnerability within regional transportation systems.

Keywords: Transportation network vulnerability; Graph representation; Road network connectivity; Toll-road infrastructure; Corridor dependency; Transportation network analysis; Central Java

1 Introduction

Primary road networks constitute critical infrastructures that sustain regional transportation systems by supporting interregional mobility, freight distribution, economic interaction, and territorial integration. As transportation systems become increasingly interconnected, disruptions occurring at strategically important road segments may propagate beyond local scales and affect wider regional accessibility and network continuity. Such conditions become particularly significant in regions characterized by constrained inland connectivity and limited routing alternatives, where mobility and logistics flows depend heavily on a relatively small number of strategic connectors. Consequently, the assessment of road network vulnerability has evolved beyond purely operational concerns and increasingly intersects with broader questions of transport resilience, regional development, and infrastructure planning [1–4].

Central Java Province, Indonesia, provides a relevant setting for examining these issues within the broader transportation system of Java Island, the country’s principal economic and demographic corridor. Located between the western and eastern regions of Java, Central Java accommodates major interregional mobility through a transportation structure shaped by contrasting physiographic conditions. The northern coastal corridor functions as a dominant logistics and economic axis, whereas inland and southern regions remain influenced by mountainous terrain and more limited interregional connectivity. During the last two decades, the expansion of the Trans-Java Toll Road system has substantially strengthened long-distance accessibility by connecting major urban and industrial regions across the island [5, 6]. However, while toll-road development is commonly associated with improved accessibility and reduced travel impedance, such expansion does not necessarily eliminate deeper structural dependency within regional transportation systems and may instead reinforce concentration around major gateway and interchange regions. From a transportation-planning perspective, this distinction is important because accessibility enhancement does not automatically imply proportional improvement in redundancy, structural robustness, or regional connectivity balance.

Graph-based modelling has become an increasingly important approach for examining the structural characteristics of transportation systems, particularly in studies concerned with connectivity, accessibility, and network vulnerability. By abstracting road systems into interconnected nodes and links, graph-based approaches enable transportation networks to be interpreted as relational structures whose configurations shape movement opportunities, accessibility organization, and corridor concentration across space [2, 7, 8]. Within this perspective, graph-theoretic measures have been widely employed to identify structurally important network components, evaluate redundancy patterns, and examine how disruptions propagate through interconnected transportation systems [4, 9]. As a result, graph-based approaches have become increasingly influential in transportation vulnerability analysis, infrastructure planning, and regional connectivity assessment.

However, the transformation of spatial road data into graph representations involves a series of modelling decisions that may substantially influence the resulting interpretation of transportation-network structure. Choices related to node definition, intersection treatment, simplification procedures, and topological correction can alter network topology, shortest-path organization, centrality distributions, and the apparent strategic importance of particular corridors or regional connectors [8, 10]. In this sense, graph construction extends beyond technical preprocessing and functions as a representational modelling process that shapes which forms of structural dependency and network vulnerability become analytically visible. Despite the growing application of graph-based methods in transportation vulnerability studies, comparatively limited attention has been directed toward how Geographic Information System (GIS)-to-network modelling choices themselves influence the interpretation of corridor concentration, connectivity structure, and the perceived effects of major infrastructure interventions such as toll-road expansion. This issue becomes particularly important in transportation systems characterized by constrained inland connectivity and geographically uneven corridor organization, where infrastructure expansion may improve accessibility while leaving deeper structural imbalances partially unresolved.

Previous studies on transportation networks have extensively examined accessibility improvement, congestion reduction, corridor efficiency, and disruption vulnerability using graph-theoretic and spatial-network approaches [2, 4, 11]. In studies of toll-road development, infrastructure expansion has often been evaluated primarily through operational and accessibility-oriented perspectives, including travel-time reduction, regional accessibility enhancement, and economic integration. However, comparatively fewer studies have examined whether toll-road expansion also alters the deeper structural organization of regional transportation systems, particularly in geographically constrained networks where redundancy remains limited. In addition, although transportation-network studies frequently rely on GIS-derived graph representations, the influence of representational modelling choices on vulnerability interpretation and corridor dependency assessment remains comparatively underexplored.

This study addresses these gaps by examining how alternative graph representations influence the interpretation of regional connectivity and structural dependency within the primary road network of Central Java, Indonesia, under scenarios with and without toll-road infrastructure. Three network representations are compared, consisting of a raw graph, an algorithmically simplified graph, and a topologically corrected graph, in order to evaluate how modelling choices affect the visibility of connectivity structure and critical transportation corridors. The analysis focuses on graph-based indicators, including weighted and unweighted average shortest path length (ASPL), betweenness centrality (BC), connected components, and articulation elements. In this study, toll roads are treated as structural transportation links within a regional connectivity framework rather than as operational traffic facilities; therefore, the analysis does not simulate traffic demand, travel behaviour, congestion, speed, or route-choice dynamics. Instead, the study examines how the structural availability of toll-road infrastructure reshapes accessibility organization and corridor dependency within the broader regional transportation system.

This study contributes to transportation-network vulnerability research in two important ways. First, it demonstrates that GIS-to-network modelling decisions should not be treated merely as technical preprocessing choices, but as representational processes that substantially influence the interpretation of structural connectivity, corridor dependency, and transportation-network vulnerability. Second, the study provides a transportation-oriented interpretation of toll-road expansion by showing that improvements in distance-based accessibility do not necessarily eliminate deeper structural dependency within regional transportation systems. More broadly, the findings contribute to ongoing discussions on transportation-network resilience, representation-aware infrastructure modelling, and the structural interpretation of regional transportation systems under geographically constrained conditions.

2 Methodology

2.1 Study Area and Road Network Data

Central Java Province is characterized by a geographically diverse transportation landscape consisting of densely connected northern coastal corridors, mountainous inland regions, and comparatively constrained southern transportation routes. As part of the broader Java transportation system, the province accommodates substantial interregional mobility and logistics flows between western and eastern Java through a combination of national arterial roads, collector corridors, and the Trans-Java Toll Network [5, 12].

The development of the Trans-Java Toll Road has been positioned as a strategic national infrastructure initiative intended to strengthen regional integration, improve logistics connectivity, and support economic development across Java Island. However, despite the expansion of high-capacity toll-road infrastructure and the resulting improvement in interregional accessibility, several inland areas within Central Java continue to rely on a relatively limited number of strategic inter-regional connectors due to topographic constraints and uneven corridor distribution. These characteristics make Central Java particularly relevant for examining how transportation network structure, corridor dependency, and toll-road integration interact within a regional-scale connectivity system. The resulting transportation configuration reflects a spatially uneven regional network structure shaped jointly by physiographic constraints and corridor-oriented infrastructure development, as illustrated in Figure 1.

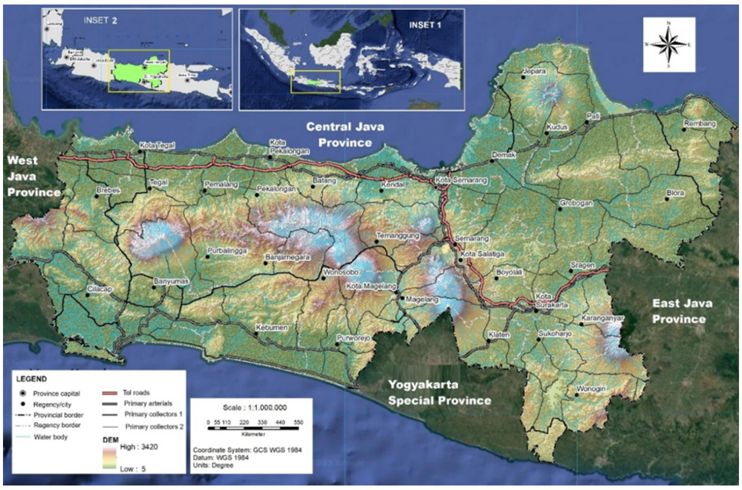

Figure 1. Primary road network of Central Java Province, Indonesia, illustrating regional corridor structure and connectivity constraints

The dataset consists of spatial road centerline data for primary arterial roads, primary collector roads, and toll roads associated with the Trans-Java Toll Network. The delineation of the primary road system follows the official Indonesian road functional hierarchy established under national and provincial road governance regulations. Within this framework, primary arterial roads and primary collector-1 corridors are designated by the national government through the Ministry of Public Works and Housing of Indonesia, while primary collector-2, collector-3, and collector-4 corridors are designated through provincial-level road network regulations issued by the Government of Central Java. Primary local roads and primary environmental roads were not included in the analysis in order to maintain focus on the regional-scale transportation backbone and inter-regional connectivity structure.

The road network dataset represents the officially designated primary road network configuration of Central Java Province in 2023 and was processed within a GIS environment prior to graph construction. Spatial road data were obtained from official Indonesian geospatial and transportation-related institutions, particularly the Geospatial Information Agency of Indonesia (Badan Informasi Geospasial), the Ministry of Public Works and Housing of Indonesia, and the Government of Central Java. Toll-road segments were explicitly identified based on official toll-road classifications and verified through comparison with provincial transportation maps and publicly available infrastructure references.

In this study, toll roads are treated as structural transportation links within the regional network rather than as operational traffic facilities. Accordingly, the analysis focuses on how the structural availability of toll-road infrastructure modifies regional connectivity patterns and structural vulnerability characteristics, without simulating traffic demand, travel speed, congestion, toll pricing, vehicle composition, or route-choice behaviour.

2.2 Graph Representation of the Road Network

To examine the influence of modelling choices on structural vulnerability assessment, three alternative graph representations of the primary road network were developed. The first representation is a raw digitization-based graph, constructed by directly converting the spatial road centerline data into a graph structure. In this representation, nodes correspond to all geometric vertices present in the dataset, including intersections, curvature points, and segmentation artefacts, while edges represent road segments between consecutive vertices.

The second representation is an algorithmically simplified graph, in which intermediate vertices associated with geometric curvature or administrative segmentation are removed while preserving network connectivity. Nodes are retained only at true road intersections and terminal points, resulting in a reduced and more compact graph that better reflects functional connectivity.

The third representation is a topologically corrected simplified graph, developed by further examining and correcting topological inconsistencies introduced during simplification, such as disconnected intersections, overlapping segments, or false dead-ends. This representation is intended to provide a functionally consistent approximation to the functional structure of the primary road network while maintaining analytical tractability. Together, these three graph models enable a systematic comparison of how graph representation choices influence the interpretation of network structure and vulnerability. The conceptual differences among the three graph representations are illustrated in Figure 2. To improve methodological transparency and reproducibility, Table 1 summarizes the principal construction rules applied to the alternative graph representations developed in this study. The comparison highlights differences in node retention, simplification strategy, topological correction, and intended structural interpretation associated with each representation.

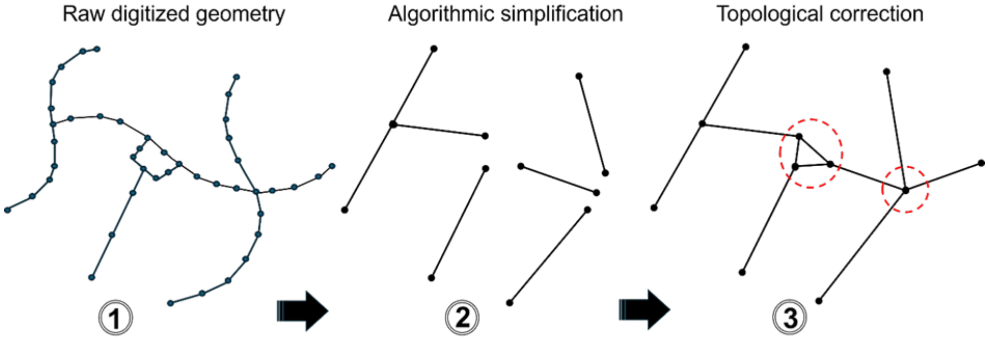

Figure 2. Transformation of the primary road network from raw digitization to a topologically corrected graph representation

2.3 Toll Road Scenarios

For each graph representation, two transportation network configurations were analyzed: a non-toll configuration, in which toll-road corridors were excluded from the regional connectivity structure, and a with-toll configuration, in which toll-road infrastructure was incorporated as functional interregional transportation links. This scenario-based approach enables the assessment of how toll-road integration modifies regional connectivity structure, corridor dependency, and structural vulnerability under different representational assumptions while maintaining consistent spatial coverage and node definitions across all graph models.

In this study, toll roads are interpreted as structural transportation links within the regional connectivity system rather than as operational traffic facilities. Accordingly, the analysis focuses on how the structural availability of toll-road infrastructure alters connectivity organization and shortest-path structure within the network, without modelling traffic demand, congestion, travel speed, toll pricing, or route-choice behaviour. The resulting graph-based transportation network configuration for the with-toll scenario is illustrated in Figure 3.

2.4 Network Vulnerability Indicators

Structural vulnerability was evaluated using four complementary graph-based indicators commonly applied in transportation network analysis: BC, articulation elements, ASPL, and the largest connected component (LCC). Together, these indicators capture both local structural criticality and global connectivity characteristics within the regional transportation network.

Table 1. Comparison of graph-construction rules under alternative network representations

Aspect	Raw Graph Representation	Algorithmically Simplified Graph	Topologically Corrected Graph
Source data	Direct Geographic Information System (GIS) road-centerline data	Simplified from the raw graph	Simplified graph with topology correction
Node definition	All geometric vertices retained	Only structural intersections and terminal nodes are retained	Structural intersections retained after connectivity correction
Intermediate curvature vertices	Retained	Removed	Removed
Road segmentation artefacts	Retained	Reduced	Corrected
Intersection treatment	Direct geometric intersections	Algorithmic intersection simplification	Topology-aware intersection correction
False dead-ends	Retained	Partially retained	Corrected
Disconnected intersections	Possible	Possible	Corrected
Overlapping/inconsistent segments	Retained	Partially simplified	Corrected
Connectivity correction	None	Limited	Applied
Intended interpretation	Raw digitized transportation graph	Compact structural graph	Functionally interpretable transportation graph
Main analytical purpose	Baseline comparison	Structural simplification	Representation-aware vulnerability interpretation

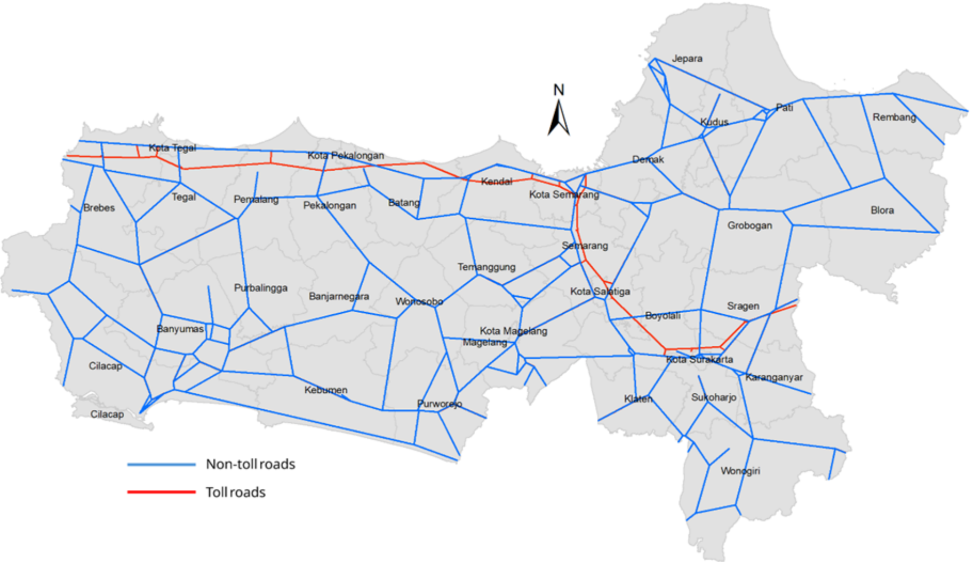

Figure 3. Topologically corrected graph representation of the Central Java primary road network incorporating toll-road infrastructure

BC was used to identify nodes located on a large proportion of shortest paths between other node pairs, reflecting their structural importance as potential transportation bottlenecks and interregional corridor connectors within the network. High BC values indicate nodes whose disruption may disproportionately affect regional accessibility and connectivity continuity.

Articulation elements were identified to detect nodes whose removal would increase the number of connected components in the network. These nodes represent structurally critical locations whose failure could fragment regional transportation connectivity and isolate portions of the network.

ASPL was employed as a global indicator of structural accessibility and connectivity organization, representing the average shortest weighted distance between all reachable node pairs. Changes in ASPL provide insight into how toll-road integration and graph representation influence regional accessibility structure and interregional transportation efficiency.

In addition to node-level and path-based indicators, the size of the LCC was used as a global structural descriptor to verify whether the transportation network remained fully connected under different graph representations and toll-road configurations. The LCC is particularly useful for identifying artificial fragmentation effects that may emerge from representational or topological modelling assumptions. The transportation-related structural interpretation associated with each network vulnerability indicator is summarized in Table 2. The formal mathematical definitions of ASPL, BC, articulation elements, and the LCC, together with details of the computational workflow, are provided in Appendix.

Table 2. Structural and transportation-network interpretation of the graph-based vulnerability indicators used in this study

Indicator	Structural Meaning	Transportation Interpretation
Betweenness centrality (BC)	Concentration of shortest paths	Potential bottlenecks and corridor dependency
Articulation Elements	Network fragmentation sensitivity	Structurally critical connectors
Average shortest path length (ASPL)	Average network path accessibility	Structural accessibility and interregional connectivity efficiency
Largest connected component (LCC)	Network integrity	Degree of overall transportation connectivity

2.5 Analysis Scale and Aggregation

The analysis was conducted at the provincial scale in order to capture system-level structural characteristics of the primary road network in Central Java. In addition, results were aggregated at the regency level to examine spatial variations in network criticality and to facilitate interpretation within a regional transportation planning context. This multi-scale approach enables the identification of both province-wide structural patterns and localized concentrations of structural vulnerability and corridor dependency.

2.6 Methodological Scope and Limitations

This study focuses exclusively on intrinsic structural vulnerability as an inherent property of transportation network topology. The analysis does not simulate hazard-induced disruptions, traffic demand, traffic assignment, capacity constraints, congestion dynamics, or travel behaviour. By isolating structural characteristics, the study provides a baseline assessment of regional transportation vulnerability that is independent of specific hazard scenarios or operational traffic conditions.

Accordingly, the resulting vulnerability interpretation should be understood as a structural assessment of regional transportation connectivity rather than as a prediction of operational traffic performance during real-world disruptions. Accordingly, the objective of the study is not to reproduce operational traffic dynamics but to examine how graph representation and toll-road integration influence the structural organization, corridor dependency, and connectivity characteristics of the regional transportation network.

3 Results

This section presents the results of the structural vulnerability analysis of the Central Java primary transportation network under alternative graph representations and toll-road configurations. The analysis is organized progressively to examine how representational modelling choices and toll-road integration influence the interpretation of regional connectivity structure, corridor dependency, and network criticality. The results are presented in three stages. First, the baseline structural characteristics of the network are examined to identify differences among the alternative graph representations and toll-road scenarios. Second, connectivity indicators are evaluated to assess how graph representation and toll-road integration influence structural accessibility and network performance. Finally, spatial aggregation at the regency level is used to examine regional patterns of transportation-network criticality and to support interpretation within a regional planning context.

3.1 Structural Characteristics of the Primary Road Network

Table 3 summarizes the structural characteristics of the Central Java primary road network under the six graph configurations developed in this study. Substantial differences are observed among the alternative graph representations, particularly between the raw digitization-based models and the simplified graph models. These differences demonstrate that graph representation substantially influences the apparent structural complexity and connectivity characteristics of the transportation network.

Table 3. Structural characteristics of the primary road network under alternative graph representations and toll road configurations

Graph Model	No. of Nodes	No. of Edges	Connected Components	LCC Size	ASPL (Unweighted)	ASPL (Weighted, m)
Model 1, raw (no toll)	12,296	12,278	>1	8625	942.65	222,073
Model 2, raw (with toll)	12,914	12,937	>1	9157	643.05	217,852
Model 3, simplified (no toll)	130	140	1	130	11.30	191,427
Model 4, simplified (with toll)	235	280	1	235	14.36	171,596
Model 5, simplified-corrected (no toll)	205	269	1	205	10.84	144,944
Model 6, simplified-corrected (with toll)	250	330	1	250	11.16	137,532

Note: LCC—largest connected component; ASPL—average shortest path length.

Graph models constructed directly from raw digitized spatial data (Models 1 and 2) contain a very large number of nodes and edges due to the inclusion of geometric curvature points, segmentation artefacts, and intermediate mapping vertices. As a result, the raw graph representations exhibit inflated network granularity that does not necessarily correspond to functional transportation intersections or meaningful corridor connectivity. The presence of numerous non-structural vertices also contributes to artificial fragmentation effects, reflected by the occurrence of multiple connected components in Model 1 despite the underlying transportation network remaining physically connected.

In contrast, the simplified and topologically corrected graph representations (Models 3–6) show a substantial reduction in network size, with the number of nodes decreasing by more than an order of magnitude relative to the raw graph models. Despite this reduction, all simplified graph configurations remain fully connected, indicating that simplification and topological correction preserve the essential regional connectivity structure of the transportation network while minimizing distortions associated with excessive geometric discretization. These results suggest that many of the apparent structural discontinuities observed in the raw graph representations originate from representational artefacts rather than from genuine transportation-network fragmentation.

Across all graph representations, the inclusion of toll roads (Models 2, 4, and 6) increases the number of nodes and edges relative to their corresponding non-toll configurations, reflecting the incorporation of additional interregional transportation corridors into the regional network structure. However, the structural effects of toll-road integration are not uniform across graph representations. In the raw graph models, toll-road inclusion substantially increases network size because the added toll corridors introduce numerous additional geometric vertices. In contrast, the simplified and corrected graph representations show more moderate structural changes, indicating that representation-aware preprocessing substantially influences the interpretation of transportation connectivity and network structure.

The inclusion of toll-road infrastructure is also associated with reductions in ASPL, particularly in the simplified and topologically corrected graph models. These reductions indicate improved structural accessibility and strengthened long-distance interregional connectivity, especially along major corridor systems such as the northern coastal transportation axis and the Semarang–Solo regional connector. Nevertheless, the reduction in ASPL does not necessarily imply a proportional reduction in structural dependency within the network. Several inland and interregional connector corridors remain structurally important despite toll-road integration, suggesting that improved accessibility may coexist with persistent concentration of regional transportation flows.

Overall, the results demonstrate that graph representation significantly conditions the interpretation of transportation-network structure and vulnerability. Simplification and topological correction do not merely reduce network size, but also substantially alter the visibility of structural connectivity patterns, corridor dependency, and apparent fragmentation within the regional transportation system.

3.2 Effects of Graph Representation and Toll Roads on Network Connectivity

The effects of graph representation and toll-road integration on regional transportation connectivity were evaluated using weighted ASPL. Because edge weights represent geometric road length, weighted ASPL reflects the average distance travelled between reachable node pairs within the regional transportation network. Table 4 summarizes the weighted ASPL values obtained for the six graph configurations developed in this study.

Table 4. Effects of graph representation and toll-road integration on regional accessibility (weighted average shortest path length (ASPL))

Model Comparison	ASPL Weighted (m)	Change (%)
Model 1 → Model 3 (algorithm)	222,073 → 191,427	−13.80
Model 3 → Model 5 (corrected)	191,427 → 144,944	−24.28
Model 4 → Model 6 (with toll)	171,596 → 137,532	−19.85
Model 5 (no toll) → Model 6 (with toll)	144,944 → 137,532	−5.11

Across all scenarios, the raw digitization-based graphs (Models 1 and 2) consistently produced substantially higher weighted ASPL values than the simplified and topologically corrected graph representations. This pattern indicates that excessive geometric segmentation inherited from raw GIS digitization tends to inflate apparent network complexity and obscure broader regional connectivity structures. Many of the accessibility limitations observed in the raw graphs, therefore, originate from representational artifacts associated with geometric subdivision rather than from actual discontinuities within the transportation system itself.

In contrast, the simplified and topologically corrected graph representations (Models 3–6) exhibit substantially lower and more stable weighted ASPL values. This reduction suggests that graph simplification and topological correction not only reduce excessive geometric granularity but also reveal a more functionally interpretable regional transportation structure. The relatively small weighted ASPL differences between the simplified and corrected graphs further indicate that topological refinement primarily improves structural consistency and connectivity interpretation rather than fundamentally altering large-scale accessibility organization.

The integration of toll-road infrastructure consistently reduced weighted ASPL across all graph representations, indicating improved long-distance accessibility and strengthened east–west transportation continuity within Central Java. However, the magnitude and visibility of this improvement vary considerably depending on the graph representation. In the raw graphs, the structural contribution of toll-road infrastructure is partially masked by excessive local segmentation and inflated topological complexity. By contrast, the simplified and topologically corrected representations reveal more coherent and regionally interpretable accessibility improvements associated with toll-road integration.

The comparative effects of graph correction and toll-road integration on weighted ASPL are illustrated in Figure 4. The figure demonstrates that reductions in apparent path distance associated with representation refinement are, in several cases, comparable to or greater than the accessibility improvements produced by toll-road inclusion itself. This finding suggests that representational assumptions may substantially influence the interpretation of transportation-network accessibility and structural connectivity.

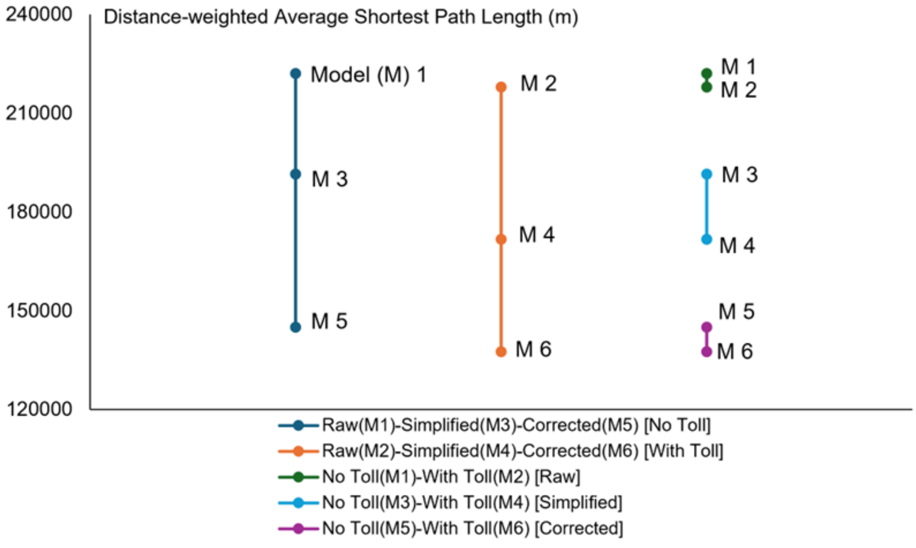

Figure 4. Weighted average shortest path length (ASPL) under alternative graph representations and toll-road configurations

The relative magnitudes of accessibility changes associated with graph correction and toll-road integration are further illustrated in Figure 5. The figure highlights that accessibility improvements produced by representation refinement can, in some cases, exceed those generated by major transportation infrastructure interventions. This result emphasizes that transportation-network accessibility interpretation is strongly conditioned by graph representation choices and may significantly influence the perceived effectiveness of infrastructure development strategies.

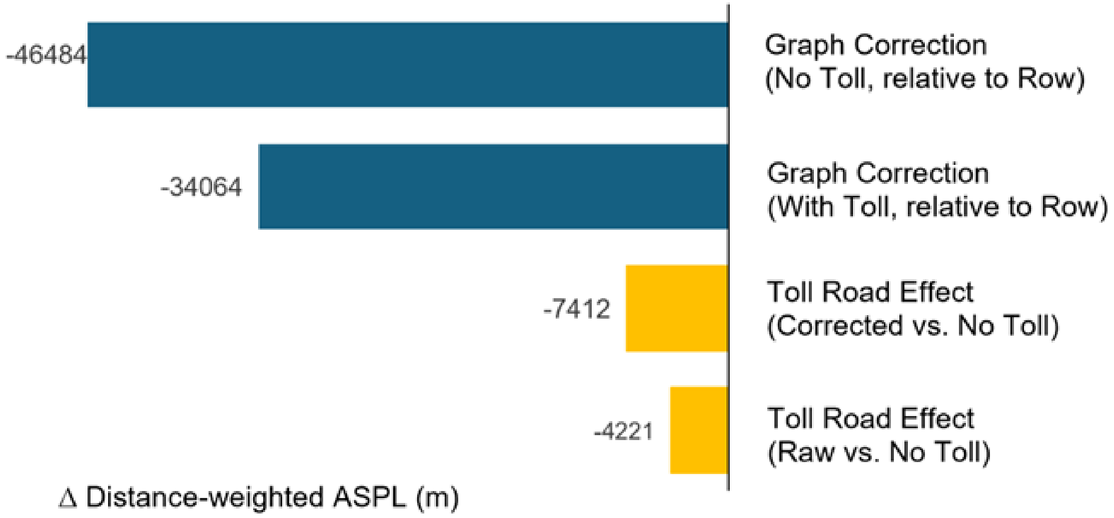

Figure 5. Relative changes in weighted average shortest path length (ASPL) under graph correction and toll-road integration

Across all graph representations, the inclusion of toll-road infrastructure consistently improves distance-based structural accessibility. Nevertheless, reduced weighted ASPL does not necessarily imply the elimination of structural dependency within the transportation network. Although toll-road integration improves interregional continuity and redistributes accessibility organization, several inland transportation corridors remain structurally important due to limited route alternatives, inherited corridor concentration, and geographically constrained regional connectivity patterns. These findings indicate that accessibility enhancement and structural redundancy do not automatically develop proportionally within regional transportation systems.

The results also demonstrate that graph representation substantially conditions the interpretation of transportation accessibility and regional connectivity structure. In the raw graph models, accessibility changes associated with toll-road integration appear more fragmented because excessive geometric segmentation artificially enlarges the apparent path structure of the network. In contrast, the simplified and corrected graph representations produce more stable and functionally interpretable accessibility patterns. These findings therefore emphasize that representation-aware graph preparation is essential for meaningful structural interpretation of transportation-network accessibility and connectivity.

3.3 Spatial Patterns of Network Criticality

While global connectivity indicators provide an overview of transportation-network performance, structural vulnerability is ultimately governed by the spatial concentration of critical nodes and corridors within the network. This subsection, therefore, examines patterns of network criticality using BC at both the node level and the aggregated regency level under alternative graph representations and toll-road configurations. Particular attention is directed toward identifying transportation corridors and regional connectors that concentrate large proportions of shortest-path flows and therefore play disproportionate roles in maintaining interregional connectivity.

3.3.1 Patterns of critical nodes based on betweenness centrality

Patterns of network criticality were first examined by identifying nodes with the highest BC values under alternative graph representations and toll-road configurations. Unlike global accessibility indicators such as ASPL, BC highlights the spatial concentration of structurally important transportation connectors through which large proportions of regional shortest-path flows are channelled.

In graph representations derived directly from raw digitization, high betweenness values tend to be distributed across a large number of nodes. Many of these nodes correspond not to functional transportation intersections, but to geometric segmentation vertices introduced during road digitization and mapping processes. As a result, shortest-path flows become artificially dispersed across numerous non-structural nodes, obscuring the identification of genuinely critical transportation connectors within the regional network. This pattern further demonstrates that raw graph representations may exaggerate local structural complexity and distort the interpretation of transportation-network criticality.

In contrast, the simplified and topologically corrected graph representations reveal a substantially more concentrated pattern of high BC. As shown in Tables 5 and 6, critically important nodes emerge along a relatively limited number of backbone transportation corridors connecting major regions within Central Java. The persistence of these nodes across alternative graph configurations suggests that their structural importance is not merely an artefact of graph representation, but rather reflects inherent characteristics of the regional transportation topology.

Table 5. Top 10 nodes with the highest betweenness centrality (BC) values in Model 5 (no toll roads)

Rank	Node ID Coordinates	Regency	Betweenness
1	385632; 9183097	Wonosobo	0.2214
2	446362; 9185918	Salatiga Municipality	0.2055
3	442950; 9186844	Salatiga Municipality	0.1929
4	434332; 9210839	Semarang	0.1884
5	435800; 9206624	Semarang	0.1869
6	378806; 9185841	Wonosobo	0.1840
7	456599; 9165825	Boyolali	0.1826
8	461441; 9236514	Demak	0.1763
9	487330; 9218070	Grobogan	0.1686
10	439424; 9230961	Semarang Municipality	0.1681

Table 6. Top 10 nodes with the highest betweenness centrality (BC) values in Model 6 (with toll roads)

Rank	Node ID Coordinates	Regency	Betweenness
1	434332; 9210839	Semarang	0.2066
2	435800; 9206624	Semarang	0.2018
3	385632; 9183097	Wonosobo	0.1867
4	456599; 9165825	Boyolali	0.1651
5	378806; 9185841	Wonosobo	0.1550
6	400819; 9194617	Temanggung	0.1527
7	470985; 9165401	Sukoharjo	0.1456
8	467581; 9165720	Bovolal	0.1420
9	478063; 9165156	Surakarta Municipality	0.1411
10	437591;9199276	Semarang	0.1392

Comparisons between non-toll and with-toll configurations further show that toll road inclusion redistributes shortest-path flows and modifies the relative ranking of certain nodes. However, several high-centrality nodes persist across both configurations, particularly in interior and mountainous areas where alternative routes remain limited. This persistence suggests that, while toll roads enhance overall network efficiency, they do not uniformly eliminate existing structural bottlenecks within the primary road network.

The spatial distribution of high-betweenness nodes shown in Figure 6 further illustrates the concentration of important transportation connectors along several inland and interregional corridors. Under the non-toll configuration, high-centrality nodes are distributed primarily along major inland connectors linking the northern coastal corridor with mountainous central regions and southern transportation routes. Under the with-toll configuration, portions of the shortest-path structure shift toward the northern toll-road corridor and associated gateway regions. Nevertheless, several inland connectors remain persistently prominent across both configurations, indicating that toll-road integration does not uniformly eliminate pre-existing structural dependency within the transportation network.

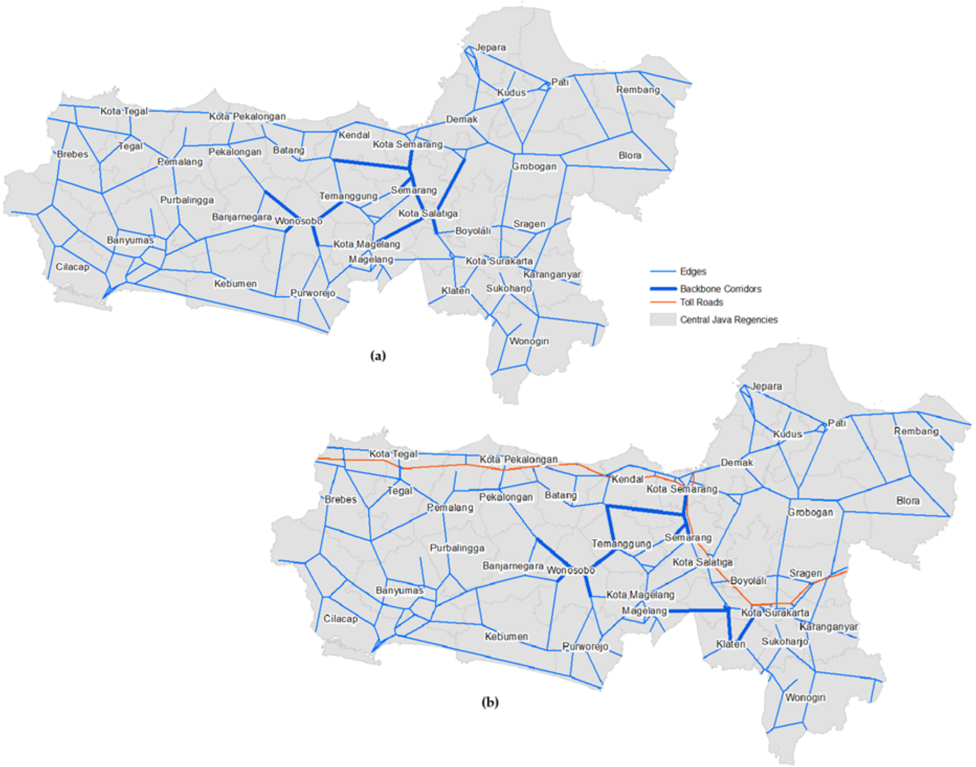

Figure 6. High-betweenness nodes in the topologically corrected graph representations of the non-toll (Model 5) and with-toll (Model 6) networks

The results further indicate that several high-centrality regions maintain their structural importance despite changes in accessibility produced by toll-road integration. Wonosobo, for example, consistently appears among the highest-ranked regions under both configurations. This persistence suggests that transportation-network criticality is not governed solely by metropolitan scale or traffic concentration, but also by geographic corridor constraints. Located within the mountainous central region of the province, Wonosobo functions as an important inland connector linking multiple interregional transportation corridors where alternative routes remain comparatively limited.

A similar pattern is observed in Boyolali and Temanggung, which remain structurally important under the with-toll configuration. These regions occupy intermediate positions connecting northern corridor systems with inland and southern areas, resulting in continued concentration of shortest-path dependency despite improvements in east–west accessibility produced by toll-road infrastructure.

Under the with-toll configuration, Semarang emerges as the most structurally prominent region within the network. This result reflects its dual role as a northern coastal transportation gateway and as a major redistribution node connecting toll-road infrastructure, inland transportation corridors, and interregional movement flows within Central Java. The strengthening of Semarang's structural prominence following toll-road integration suggests that high-capacity infrastructure may reinforce existing gateway concentration patterns rather than uniformly distributing regional connectivity.

Comparisons between Tables 5 and 6 further indicate that toll-road integration modifies the relative ranking and magnitude of node-level betweenness values without fundamentally altering the spatial structure of transportation-network criticality. Several high-centrality inland connectors remain persistent across both configurations, particularly in geographically constrained areas where route alternatives remain finite. These findings suggest that improvements in regional accessibility may coexist with continued concentration of structural dependency within a limited number of transportation corridors.

The persistence of structural dependency patterns under both toll-road configurations is further illustrated by the BC distributions shown in Figure 7. The figure shows that toll-road integration generally reduces the magnitude of BC among the most critical nodes, indicating partial redistribution of shortest-path flows across the transportation network. However, the overall distribution pattern remains comparatively similar between the non-toll and with-toll configurations. This result suggests that toll-road infrastructure modifies the intensity of structural dependency without fundamentally eliminating the concentration of connectivity within a relatively limited number of strategically important transportation corridors.

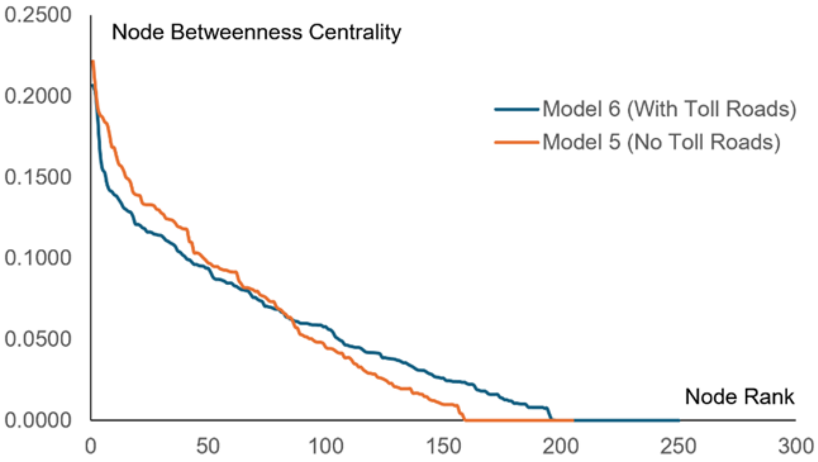

Figure 7. Betweenness centrality (BC) distributions for the topologically corrected graph representations of Model 5 (non-toll) and Model 6 (with toll)

The articulation analysis further reinforces this interpretation by indicating that several inland connectors function not only as high-centrality transportation nodes, but also as structurally sensitive transition points whose disruption may fragment portions of the regional transportation network. This pattern is particularly evident within geographically constrained inland corridors where alternative cross-regional routes remain limited, suggesting that corridor dependency in Central Java is associated not only with concentrated shortest-path organization, but also with reduced structural redundancy.

Table 7 further summarizes the articulation-point characteristics identified under the simplified and topologically corrected graph representations. The results indicate that graph representation substantially influences the apparent structural fragility of the transportation network. The algorithmically simplified graphs exhibit very high articulation-point proportions, suggesting excessive concentration of structural dependency caused by over-simplified corridor aggregation. In contrast, the topologically corrected graph representations produce substantially lower articulation-point ratios, indicating the restoration of more realistic redundancy and connectivity patterns within the regional transportation structure.

Table 7. Articulation-point characteristics under alternative graph representations and toll-road configurations

Rank	Node ID Coordinates	Regency	Betweenness
1	434332; 9210839	Semarang	0.2066
2	435800; 9206624	Semarang	0.2018
3	385632; 9183097	Wonosobo	0.1867
4	456599; 9165825	Boyolali	0.1651
5	378806; 9185841	Wonosobo	0.1550
6	400819; 9194617	Temanggung	0.1527
7	470985; 9165401	Sukoharjo	0.1456
8	467581; 9165720	Bovolal	0.1420
9	478063; 9165156	Surakarta Municipality	0.1411
10	437591;9199276	Semarang	0.1392

Interestingly, toll-road integration substantially improves weighted accessibility while producing only marginal changes in articulation-point proportions within the topologically corrected graph models. This result suggests that accessibility enhancement and structural robustness do not necessarily develop proportionally within regional transportation systems. Although toll-road infrastructure strengthens long-distance continuity and redistributes shortest-path organization, several inland transportation connectors remain structurally sensitive due to geographically constrained corridor organization and limited alternative routing structures.

3.3.2 Regency-level aggregation of betweenness centrality

To support interpretation at the regional planning scale, node-level BC values were aggregated at the regency and municipality level. This aggregation provides a broader spatial perspective on how structural dependency is distributed across administrative regions and enables identification of areas whose transportation connectivity plays disproportionately important roles in maintaining network-wide continuity.

Tables 8 and 9 summarize the top-ranked regencies and municipalities based on maximum and mean BC values under the simplified and topologically corrected graph representations for the non-toll and with-toll configurations, respectively. Compared with the raw digitization-based graphs, the simplified and corrected graph representations produce a smaller and more clearly differentiated subset of high-centrality regions. This contrast reflects the concentration of structural criticality observed after representation-aware graph preparation and enables clearer identification of genuinely important transportation connectors.

Table 8. Top 10 regencies/municipalities with the highest maximum betweenness centrality (BC) values in Model 5 (simplified, corrected, no toll roads)

Regency	Max. Betweenness	Mean Betweenness	Number of Nodes
Wonosobo	0.2214	0.1515	5
Salatiga Municipality	0.2055	0.1992	2
Semarang	0.1884	0.1279	6
Boyolali	0.1826	0.1268	4
Demak	0.1763	0.1053	3
Grobogan	0.1686	0.0986	8
Semarang Municipality	0.1681	0.0941	5
Sukoharjo	0.1579	0.0620	7
Surakarta Municipality	0.1567	0.1082	4
Purworejo	0.1541	0.0737	9

Table 9. Top 10 regencies/municipalities with the highest maximum betweenness centrality (BC) values in Model 6 (simplified, corrected, with toll roads)

Regency	Max. Betweenness	Mean Betweenness	Number of Nodes
Semarang	0.2066	0.1021	12
Wonosobo	0.1867	0.1204	5
Boyolali	0.1651	0.0940	7
Temanggung	0.1527	0.0638	9
Sukoharjo	0.1456	0.0534	7
Surakarta Municipality	0.1411	0.0919	4
Semarang Municipality	0.1339	0.0793	11
Purworejo	0.1311	0.0605	9
Salatiga Municipality	0.1301	0.0862	4
Pekalongan	0.1211	0.0839	3

Under the non-toll configuration, regencies such as Wonosobo, Semarang, Boyolali, Demak, and Grobogan exhibit consistently high centrality values, indicating the presence of structurally important transportation connectors within their administrative boundaries. Many of these regions are located either along major backbone transportation corridors or at strategic junctions linking the northern coastal corridor, mountainous inland regions, and southern parts of the province.

The with-toll configuration modifies the relative ranking and magnitude of several regional centrality values. Semarang becomes the most structurally prominent regency, while regions associated with major toll-road gateways and redistribution corridors, including Sukoharjo and Surakarta Municipality, also increase in relative importance. However, several inland regions, including Wonosobo and Boyolali, remain consistently prominent despite the introduction of toll-road infrastructure. This persistence indicates that toll-road integration modifies accessibility organization without fundamentally dissolving underlying inland corridor dependency within the regional transportation system.

Overall, the persistence of several high-centrality regions across alternative network configurations indicates that regional structural vulnerability in Central Java remains closely associated with the topology of inland and interregional transportation corridors shaped by physiographic constraints. Although toll-road infrastructure strengthens long-distance accessibility and improves east–west interregional continuity, accessibility gains continue to coexist with concentrated dependency on a relatively limited number of inland connectors and gateway corridors.

4 Discussion

This study examined the structural connectivity and vulnerability characteristics of the primary transportation network in Central Java by explicitly considering graph representation choices and toll-road integration within a regional transportation framework. Rather than proposing new vulnerability metrics, the analysis focused on how representational modelling assumptions condition the interpretation of accessibility organization, corridor dependency, and network criticality, as well as the perceived structural contribution of major transportation infrastructures. The following discussion synthesizes the main findings by situating them within broader discussions on transportation-network vulnerability, regional accessibility structure, and representation-aware transportation-network assessment.

4.1 Graph Representation as a Conditioning Factor in Road Network Vulnerability Assessment

A central finding of this study is that graph representation substantially conditions the interpretation of road transportation-network connectivity and structural vulnerability. The results demonstrate that graph construction should not be treated merely as a technical preprocessing procedure, but rather as a representational modelling process that directly influences the visibility of corridor dependency, structural fragmentation, accessibility organization, and network criticality within regional transportation systems.

The comparison between the raw digitization-based graphs and the simplified and topologically corrected representations shows that direct conversion of GIS road centerline data into graph structures may inherit substantial geometric artefacts from the original spatial dataset. Curvature vertices, segmentation points, divided carriageways, and disconnected intersections introduce large numbers of non-functional intermediate nodes that artificially inflate apparent network complexity and distort shortest-path organization. As observed in the raw graph configurations, these artefacts disperse BC across numerous geometric vertices and exaggerate accessibility limitations through artificially elongated path structures, thereby obscuring the identification of genuinely critical transportation corridors.

Concerns regarding the distortion of topological indicators caused by geometric digitization and graph construction procedures have long been recognized in spatial-network analysis and urban street-network studies. Previous studies have shown that transportation-network indicators are sensitive to how spatial systems are abstracted into graph structures, particularly when geometric vertices are treated equivalently to functional intersections [7, 9, 13, 14]. Similar concerns have also been discussed in broader studies of spatial and transportation-network representation, where graph abstraction influences the interpretation of connectivity, accessibility, and structural organization [8, 10, 15].

By contrast, the simplified and topologically corrected graph representations reveal a more coherent and functionally interpretable regional transportation structure. The substantial reduction in weighted ASPL following graph refinement indicates that simplification and topological correction improve the interpretability of the regional accessibility organization by removing artificial discontinuities embedded within raw GIS-derived network structures. Importantly, the relatively small differences between the simplified and corrected graph models suggest that topological correction primarily strengthens structural consistency and connectivity interpretation rather than fundamentally altering the broader regional accessibility pattern.

The comparative analysis presented in Figures 4 and 5 further demonstrates that representational refinement may influence accessibility interpretation as strongly as major infrastructure interventions. In several cases, the reduction in weighted ASPL associated with graph correction exceeded the additional reduction produced by toll-road inclusion. This finding suggests that transportation accessibility is not interpreted independently from the modelling framework through which the network is constructed. Consequently, transportation-vulnerability assessments relying on graph-based representations should explicitly acknowledge the influence of graph preparation choices on the resulting interpretation of accessibility structure, corridor dependency, and regional connectivity organization.

The present study extends these concerns by demonstrating that representation-related distortions may substantially influence regional transportation vulnerability interpretation and, in some cases, produce effects larger than those associated with major infrastructure interventions themselves. Although toll-road integration improves long-distance accessibility and strengthens east–west regional continuity, the broader structural organization of the transportation network remains strongly conditioned by the underlying topology of inland and interregional transportation corridors. In this context, graph representation influences not only the numerical magnitude of network indicators but also the perceived structural contribution of transportation infrastructure within the regional connectivity system.

These findings carry implications beyond methodological preprocessing alone. Within regional transportation-network analysis, graph representation effectively determines which structural relationships become analytically visible and which vulnerabilities remain concealed within the abstraction process itself. This issue becomes particularly important in regional systems characterized by constrained inland connectivity, geographically uneven corridor organization, and limited routing alternatives, such as those observed in Central Java. Under such conditions, representation-aware graph preparation becomes essential not only for computational consistency but also for meaningful structural interpretation of transportation vulnerability.

Rather than proposing new graph-theoretic indicators, this study contributes by reframing how existing network measures should be interpreted within regional road transportation systems. Structural vulnerability emerges not solely as a property of physical infrastructure, but also as an outcome conditioned by how transportation systems are abstracted into graph representations. Despite its importance, this representational dimension remains comparatively underexplored within transportation-vulnerability studies, particularly in analyses of regional-scale infrastructure systems in developing and geographically constrained contexts.

4.2 Toll Roads as Structural Modifiers Rather than Structural Solutions

The results of this study indicate that toll-road infrastructure substantially improves regional transportation accessibility, particularly by strengthening long-distance east–west continuity along the northern corridor system and the Trans-Java transportation axis. These improvements are reflected by consistent reductions in weighted ASPL across all graph representations, especially within the simplified and topologically corrected network models, where toll-road corridors emerge as continuous interregional transportation links. Similar accessibility gains associated with high-capacity transportation infrastructure have been widely discussed in transportation-network studies, emphasizing the role of corridor expansion in improving regional mobility and connectivity efficiency [16–18].

Within the context of Java Island, the structural prominence of toll-road corridors is also consistent with broader regional transportation observations regarding the strategic role of the Trans-Java transportation system in supporting logistics integration, interregional mobility, and economic interaction along the northern corridor of Java [12]. The rapid expansion of toll-road infrastructure across Java has substantially strengthened long-distance continuity between major urban and industrial regions, while simultaneously reinforcing the concentration of mobility and freight movement along several dominant transportation axes. Similar tendencies have also been noted in recent Indonesian studies discussing the spatial and socioeconomic implications of toll-road development and corridor concentration [19, 20].

However, the results also demonstrate that improved accessibility does not necessarily imply proportional reductions in structural dependency or transportation-network vulnerability. Despite the inclusion of toll-road infrastructure, several inland and interregional connectors remain persistently prominent across alternative configurations, particularly within mountainous and geographically constrained regions where route alternatives remain comparatively limited. The persistence of high-centrality regions such as Wonosobo and Boyolali suggests that toll-road expansion modifies accessibility organization without fundamentally dissolving the inherited concentration of structural dependency embedded within the regional transportation topology.

This distinction between accessibility improvement and structural robustness becomes particularly important within regional transportation systems characterized by uneven corridor distribution and strong physiographic constraints. While toll roads increase travel efficiency and strengthen major interregional continuity, they do not automatically generate redundancy within inland transportation structures where connectivity remains concentrated along a limited number of strategically important corridors. Similar tensions between efficiency enhancement and persistent structural vulnerability have been discussed in transportation resilience and vulnerability studies, where infrastructure expansion may redistribute flows while maintaining geographically uneven dependency on specific nodes or corridors [4, 21, 22].

The regional patterns identified in Central Java further reinforce this interpretation. Under the with-toll configuration, Semarang emerges as the dominant structural gateway within the regional transportation system, reflecting its dual role as a northern coastal logistics hub and as a redistribution node connecting toll-road infrastructure, inland corridors, and interregional transportation flows. This finding aligns with broader transportation observations regarding the importance of the northern coastal corridor and Semarang's strategic position within Java's logistics and mobility structure. At the same time, several inland regions continue to exhibit strong structural prominence despite the strengthening of toll-road continuity along the northern axis.

The persistence of inland structural dependency is particularly relevant in geographically heterogeneous regions such as Central Java, where mountainous terrain and finite interregional crossing corridors constrain the availability of alternative transportation routes. Under such conditions, several inland connectors naturally maintain disproportionately important structural roles within the regional network because connectivity between northern, central, and southern regions depends on a relatively limited number of viable transportation corridors. Similar geographically concentrated transportation dependencies have also been reported in regional transportation-network studies conducted in other constrained topographic settings, including Indonesian regional road systems characterized by uneven corridor distribution and limited redundancy [23, 24].

The articulation-point analysis further reinforces this interpretation. Although toll-road integration substantially improves weighted accessibility, articulation-point proportions within the topologically corrected graph representations change only marginally after toll-road inclusion. This result suggests that accessibility enhancement does not necessarily eliminate deeper structural dependency within geographically constrained regional transportation systems.

An additional implication emerging from this study is that the perceived structural contribution of toll-road infrastructure is itself sensitive to graph representation choices. Under raw digitization-based graph models, the structural effects of toll-road inclusion appear comparatively muted because excessive geometric segmentation obscures large-scale corridor organization. In contrast, the simplified and topologically corrected graph representations reveal both the accessibility benefits and the structural limitations of toll-road integration more clearly. This finding further reinforces the importance of representation-aware graph preparation when interpreting the structural implications of major transportation infrastructure interventions.

Overall, the findings suggest that transportation infrastructure expansion should not be interpreted solely through the lens of accessibility improvement. Although toll roads substantially strengthen regional mobility and long-distance continuity, complementary strategies aimed at improving redundancy, alternative routing, and inland corridor resilience remain necessary to address persistent structural dependency within regional transportation systems.

4.3 Spatial Concentration of Criticality and Regional Transportation Structure

The results of this study reveal a pronounced spatial concentration of structural criticality within the Central Java transportation network. Both node-level and regency-level analyses consistently identify a relatively limited number of corridors and connectors that accommodate disproportionately large portions of regional shortest-path organization. This concentration pattern indicates that regional connectivity is not distributed uniformly across the network but instead depends strongly on several strategically positioned transportation corridors and gateway regions.

The simplified and topologically corrected graph representations reveal these concentration patterns more clearly than the raw digitization-based models. After excessive geometric discretization is removed, high-centrality nodes become concentrated along a relatively limited number of backbone transportation corridors linking the northern coastal region, inland mountainous areas, and southern parts of the province. This result further supports the argument that representation-aware graph preparation is necessary not only for computational consistency but also for meaningful interpretation of regional transportation vulnerability and corridor dependency.

One of the most important findings is the persistence of several inland transportation connectors across both non-toll and toll configurations. Regions such as Wonosobo, Boyolali, and Temanggung remain structurally prominent despite substantial improvements in east–west accessibility associated with toll-road integration. This persistence suggests that structural criticality within the regional transportation network is governed not only by metropolitan concentration or traffic intensity, but also by inherited corridor organization and geographic constraints that limit the availability of alternative routes.

Within the context of Central Java, this pattern is closely related to the province's physiographic structure and uneven transportation corridor distribution. Mountainous inland regions naturally constrain cross-regional connectivity and reduce routing flexibility, causing several inland connectors to maintain disproportionately important structural roles within the transportation system. The continued prominence of Wonosobo, for example, aligns with regional planning and transportation-development documents describing the regency as a geographically constrained upland connector characterized by mountainous terrain, limited east–west crossing alternatives, and repeated infrastructure proposals aimed at strengthening regional accessibility [25, 26]. Under such conditions, shortest-path organization tends to concentrate along a relatively small number of viable inland corridors, even after substantial accessibility improvements along the northern toll-road axis.

Similar interpretations apply to Boyolali and Temanggung, which continue to function as structurally important intermediate connectors between northern corridor systems, inland transportation routes, and southern regional movements. Regional transportation and spatial-planning documents indicate that Boyolali occupies an important redistribution position along the Semarang–Solo transportation axis while simultaneously connecting inland movements toward Magelang and the surrounding upland regions [27, 28]. Temanggung exhibits a comparable structural role within the inland Kedu transportation system, where movement corridors remain strongly conditioned by basin morphology and mountainous physiographic constraints [29]. These contextual correspondences suggest that the identified high-centrality regions reflect not only graph-theoretic properties, but also physically and institutionally recognized transportation structures within Central Java. Similar geographically concentrated transportation dependencies have also been discussed in transportation vulnerability studies emphasizing constrained corridor organization and uneven redundancy distribution within regional-scale transportation systems [4, 30].

At the same time, the with-toll configuration reinforces the structural prominence of several gateway regions, particularly Semarang. Under the toll-integrated network structure, Semarang emerges as the dominant structural gateway within the regional transportation system, reflecting its dual role as a northern coastal logistics hub and as a redistribution node connecting toll-road infrastructure, inland transportation corridors, and interregional transportation flows. This finding aligns with broader regional transportation observations describing the northern coastal corridor and the Trans-Java transportation system as the principal logistics and mobility backbone of Java Island [12, 28, 31].

The strong structural prominence of Semarang identified in the graph analysis also corresponds closely with its documented role within the regional transportation system of Java. Provincial and metropolitan planning documents consistently position Semarang as the principal northern coastal gateway of Central Java, integrating the Trans-Java toll corridor, Tanjung Emas Port, Ahmad Yani International Airport, and major metropolitan redistribution functions within the Kedungsepur region [12, 32]. At the same time, the Semarang–Demak corridor has increasingly been recognized as a strategically critical yet environmentally vulnerable transportation corridor due to recurrent tidal flooding, coastal subsidence, and concentrated logistics dependency along the northern coastal plain [33, 34]. These conditions suggest that the high-centrality patterns identified in the present study correspond not only to abstract network topology, but also to real regional concentrations of mobility, logistics activity, and infrastructure dependency.

The concentration of structural prominence around Semarang also reflects broader tendencies of corridor consolidation associated with major transportation infrastructure development. As high-capacity toll-road infrastructure strengthens long-distance continuity along the northern corridor, major gateway regions connected to these systems become increasingly important as redistribution and interchange nodes. Similar concentration effects associated with high-capacity transportation corridors have been observed in previous transportation-network studies examining the structural implications of corridor expansion and network hierarchy formation [17].

Importantly, however, the strengthening of gateway regions does not eliminate the persistence of inland structural dependency. As illustrated by the BC distributions shown in Figure 7, toll-road integration reduces the magnitude of several high-centrality nodes and redistributes portions of shortest-path organization, but does not fundamentally dissolve the concentration of structural dependency within a relatively limited number of strategically important transportation corridors. This distinction suggests that improvements in regional accessibility and mobility efficiency may coexist with persistent concentration of transportation-network criticality.

Overall, the findings indicate that structural vulnerability within regional transportation systems should be interpreted not solely through aggregate accessibility indicators, but also through the spatial organization of corridor dependency and gateway concentration embedded within the network topology itself. In geographically heterogeneous transportation systems such as Central Java, structural criticality remains strongly shaped by physiographic constraints, inherited corridor organization, and finite interregional crossing routes, even under conditions of substantial transportation infrastructure expansion.

4.4 Implications for Representation-Aware Transport Planning and Vulnerability Analysis

The findings of this study carry several implications for regional transportation planning and transportation-network vulnerability assessment, particularly in geographically heterogeneous regions characterized by uneven corridor distribution and limited routing redundancy. Most importantly, the results suggest that improvements in accessibility should not automatically be interpreted as proportional reductions in structural vulnerability. Although toll-road infrastructure substantially strengthens regional mobility and long-distance continuity within the Central Java transportation system, several inland and interregional connectors remain persistently important due to inherited corridor dependency and physiographic constraints.

This distinction is particularly relevant for transportation planning practices that prioritize accessibility enhancement primarily through expansion of high-capacity transportation corridors. While such infrastructure may significantly improve regional efficiency and economic integration, the results indicate that structurally important inland connectors and alternative regional corridors continue to play critical roles in maintaining network continuity and resilience. In regions characterized by mountainous terrain and finite interregional crossing routes, transportation vulnerability may remain concentrated within a limited number of strategically important corridors despite substantial infrastructure expansion.

Within the context of Central Java, these findings suggest that transportation-network strengthening should not rely exclusively on the expansion of dominant corridor systems such as the Trans-Java toll-road axis. Complementary investments aimed at improving inland connectivity, increasing route redundancy, and strengthening secondary interregional corridors may remain important for reducing persistent structural dependency within the regional transportation system. Similar concerns regarding geographically uneven transportation dependency and corridor concentration have also been discussed in regional transportation resilience and connectivity studies emphasizing the importance of redundancy and alternative routing structures [4, 22].

The study also highlights the importance of representation-aware modelling practices within transportation-network analysis. The results demonstrate that graph preparation procedures strongly influence the interpretation of accessibility, corridor dependency, and structural criticality. Under raw digitization-based graph representations, excessive geometric segmentation obscures large-scale transportation structure and may distort vulnerability interpretation. In contrast, representation-aware graph simplification and topological correction reveal functionally meaningful transportation patterns more clearly and allow more reliable interpretation of regional connectivity organization.

These findings suggest that graph representation should be treated as an integral methodological consideration within transportation-network studies rather than as a purely technical preprocessing step. This issue becomes particularly important in regional-scale analyses where transportation systems are abstracted from GIS datasets containing substantial geometric detail and varying levels of topological consistency. Without careful representation-aware preparation, graph-based transportation indicators may reflect artefacts of spatial digitization more strongly than the functional structure of the transportation network itself.

At a broader level, the study contributes to ongoing discussions regarding the interpretation of transportation-network vulnerability beyond purely operational perspectives. Rather than focusing exclusively on traffic disruption or post-disaster performance, the present study emphasizes vulnerability as an intrinsic structural property embedded within regional transportation topology and corridor organization. Under this perspective, transportation disruptions do not necessarily create vulnerability, but instead reveal structural dependency patterns that already exist within the network configuration itself.

4.5 Positioning within Representation-Aware Transportation Vulnerability Studies

This study contributes to the transportation-network vulnerability literature by emphasizing the importance of graph representation as a conditioning factor in the interpretation of regional transportation structure and structural vulnerability. Previous transportation vulnerability studies have extensively examined network criticality, accessibility disruption, redundancy, and resilience using graph-based approaches [3, 16, 17, 30]. However, comparatively less attention has been directed toward how representational modelling assumptions embedded within graph construction may influence the interpretation of these indicators themselves.

Within studies examining the structural implications of major transportation infrastructure, toll-road development is commonly associated with improved accessibility, regional integration, and increased transportation efficiency [12, 18]. The findings of the present study support these observations, but further suggest that accessibility enhancement may coexist with persistent structural dependency concentrated within geographically constrained inland corridors and major gateway regions. Under this perspective, toll-road infrastructure operates not only as an accessibility-enhancing system but also as a structural modifier that reshapes the organization of regional transportation dependency.

The study also contributes to emerging discussions linking transportation-network analysis with geographically grounded regional interpretation. Rather than treating graph indicators as purely abstract topological measures, the present analysis situates structural vulnerability within the physiographic and corridor organization context of Central Java, thereby connecting graph-based transportation analysis with regional transportation geography and infrastructure planning perspectives.

Overall, the findings suggest that meaningful interpretation of regional transportation vulnerability requires simultaneous consideration of graph representation, infrastructure structure, and regional transportation organization. In this sense, the study positions itself not as a proposal of new vulnerability metrics but as a representation-aware interpretation framework for understanding structural dependency within regional transportation systems.

5 Conclusions

This study examined the intrinsic connectivity structure and structural vulnerability of the primary transportation network in Central Java by explicitly considering graph representation choices and toll-road integration within a regional-scale transportation system. Through comparison of raw digitization-based, simplified, and topologically corrected graph representations under non-toll and with-toll configurations, the results demonstrate that both transportation infrastructure structure and representational modelling assumptions substantially influence the interpretation of regional connectivity and structural vulnerability.

The findings show that graph representation strongly conditions the visibility of accessibility organization, corridor dependency, and network criticality within regional transportation systems. Raw digitization-based graph models inherit substantial geometric artefacts that obscure large-scale corridor organization and distort the interpretation of shortest-path structure and critical-node concentration. In contrast, representation-aware graph preparation reveals more stable and functionally interpretable transportation structures, indicating that graph construction should be treated as an integral methodological component of transportation-network vulnerability assessment rather than merely as a technical preprocessing step.

The study also demonstrates that toll-road infrastructure substantially improves regional accessibility and strengthens long-distance continuity along the northern transportation corridor and the Trans-Java system. However, these improvements do not uniformly eliminate structural dependency within the regional transportation network. Several inland and interregional connectors remain persistently important across alternative configurations, particularly within geographically constrained areas characterized by finite route alternatives and uneven corridor distribution. This result suggests that accessibility enhancement and structural robustness should not be interpreted as automatically equivalent within regional transportation systems.

Within the context of Central Java, the findings further indicate that transportation vulnerability remains strongly conditioned by the interaction between physiographic structure, inherited corridor organization, and transportation topology. Major gateway regions such as Semarang become increasingly prominent following toll-road integration, while inland connectors within mountainous regions continue to maintain disproportionately important structural roles. These patterns highlight the importance of considering both regional transportation geography and representation-aware modelling practices when interpreting transportation-network vulnerability and infrastructure intervention effects.

Overall, the study contributes by demonstrating how representational assumptions influence the interpretation of transportation-network structure and vulnerability within the regional transportation framework. The findings suggest that meaningful transportation-network vulnerability assessment requires simultaneous consideration of graph representation, infrastructure organization, and regional transportation context. Future research may extend this perspective by integrating structural analysis with operational transportation dynamics, hazard exposure modelling, and temporal network transformation processes within evolving regional infrastructure systems.

Author Contributions

Conceptualization, B.K., M.I.R., B.B., and A.A; methodology, B.K. and M.I.R; software, B.K.; validation, B.K. and M.I.R.; formal analysis, B.K.; writing—original draft preparation, B.K.; writing—review and editing, M.I.R, B.B, and A.A.; visualization, B.K.; supervision, M.I.R, B.B., and A.A.; All authors have read and agreed to the published version of the manuscript.

Data Availability

The data used in this study were obtained from official government sources, including the Ministry of Public Works and Housing of Indonesia and the Central Java Provincial Government. The processed network datasets and analytical results are available from the corresponding author upon reasonable request.

Acknowledgements

The authors would like to thank the Ministry of Public Works and Housing of Indonesia and the Central Java Provincial Government for providing access to the primary road network datasets used in this study.

Conflicts of Interest

The authors declare no conflicts of interest.

Declaration on the Use of Generative AI and AI-assisted Technologies

During the preparation of this manuscript, the authors used ChatGPT (OpenAI) for language refinement and editorial assistance. All scientific interpretation, analysis, and conclusions remain the responsibility of the authors.

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Appendix

Network Indicators and Computational Environment

This appendix provides the formal definitions of the network indicators employed in the analysis and a brief description of the computational environment used for graph construction and analysis.

1. Average Shortest Path Length

Let $G = (V, E)$ be a connected graph, where V denotes the set of nodes and E denotes the set of edges. The ASPL is defined as in Eq. (A1):

$$\text{ASPL} = \frac{1}{|V|(|V|-1)} \sum_{i \neq i \in V} d(i,j) \tag{A1}$$

where, $d(i,j)$ represents the length of the shortest path between nodes i and j.

In this study, two formulations of ASPL were employed, i.e., unweighted ASPL (where each edge has unit weight, representing topological distance) and distance-weighted ASPL (where edge weights correspond to physical road segment length in meters, representing geographical travel distance). The weighted formulation is used as the primary indicator of network efficiency at the regional scale.

2. Betweenness Centrality

BC quantifies the importance of a node in terms of its participation in shortest paths between other node pairs. The BC of a node $v \in V$ is defined in Eq. (A2):

$$\text{BC}(v) = \sum_{s \neq v \neq t \in V} \frac{\sigma_{st}(v)}{\sigma_{st}} \tag{A2}$$

where, σ_{st} is the total number of shortest paths between nodes s and t, and $\sigma_{st}(v)$ is the number of those paths that pass through node v. Nodes with high BC values are interpreted as structurally critical elements whose failure may disproportionately disrupt network-wide connectivity.

3. Articulation Points

An articulation point (also referred to as a cut vertex) is defined as a node whose removal increases the number of connected components in the graph. Formally, a node $v \in V$ is an articulation point if (Eq. (A3))

$$|C(G - v)| > |C(G)| \tag{A3}$$

where, $C(G)$ denotes the number of connected components of graph G, and $G - v$ denotes the graph obtained by removing node v and all incident edges. Articulation points represent structurally vulnerable locations whose failure may fragment the network into disconnected sub-networks.

4. Largest Connected Component

In an undirected graph $G = (V, E)$, a connected component is defined as a maximal subgraph in which any two nodes are connected by at least one path. The LCC refers to the connected component with the maximum number of nodes.

Formally, if C_l, C_2, …, C_k denote the connected components of graph G, then the LCC is defined as in Eq. (A4).

$$\mathrm{LCC} = \max_{i=1,\ldots,k} |C_i| \tag{A4}$$

where, $|\mathrm{C}_i|$ denotes the number of nodes in component C_i. In this study, LCC size is used as a structural descriptor to verify whether the network remains globally connected under different graph representations and toll road configurations, and to identify potential fragmentation effects introduced by modelling assumptions.

5. Computational Environment

All network modelling and analysis were conducted using a Python-based computational environment. The spatial road network was processed in a GIS environment and converted into graph representations using custom scripts. Graph construction, simplification, and topological correction were implemented using standard network analysis libraries, while shortest path and centrality computations were performed using graph-theoretic algorithms.

The analysis workflow consists of: spatial preprocessing and network extraction in GIS; graph construction from road centerline data; algorithmic simplification and topological correction; scenario generation (non-toll and with-toll configurations); computation of ASPL, BC, and articulation points; spatial aggregation at the regency level. This workflow ensures reproducibility and consistency across alternative graph representations and scenario configurations.