Assignment 4
Network Analysis-Driven Simulation
Advanced Simulation

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1 Introduction

Bangladesh's multi-modal transport network plays a central role in supporting economic activity, particularly through the movement of goods via road-based freight. The national road system connects production centers, consumption zones, industrial areas, and major ports. A large share of cargo is transported by trucks, making the road network not only functionally critical, but also economically indispensable. However, the reliability of this network is routinely challenged by Bangladesh's high exposure to natural hazards, including floods, cyclones, heavy rainfall, and landslides. These events disrupt connectivity and can significantly impact trade, mobility, and supply chain resilience.

This study aims to assess the *criticality* and *vulnerability* of Bangladesh's road network infrastructure, with a specific focus on road segments and bridges involved in truck-based cargo transport. Criticality is understood as the economic importance of road segments under normal operating conditions, while vulnerability relates to the risk of disruption due to external hazards and the fragility of structural components, such as bridges. The overarching goal is to identify the most essential and at-risk components of the network, enabling more informed infrastructure planning and resilience-building interventions.

The analysis is based on data from the Road Maintenance and Management System (RMMS), which provides vehicle-specific traffic counts at chainage-based intervals, including data for heavy, medium, and small trucks. Additionally, bridge condition data was sourced from the BMMS (Bridge Maintenance Management System) dataset, while hazard exposure information was obtained from the United Nations' INFORM Subnational Risk Index for Bangladesh (*Bangladesh INFORM Sub-National Risk Index 2022* 2022).

To conduct this analysis, we adopt a structured approach that evaluates the road network from two complementary perspectives: criticality and vulnerability. These concepts provide insight not only into which roads are most economically significant, but also into which ones are most susceptible to failure in the face of external hazards.

The concept of criticality is explored by examining how central and heavily used each road segment is, especially for freight transport. We measure this using a weighted combination of three factors: the normalized traffic volume, the network's betweenness centrality, and the proportion of truck traffic relative to total traffic. This approach is informed by the work of Bramka Arga Jafino 2021, who argue that a composite view of traffic intensity, flow centrality, and economic contribution provides a more accurate picture of freight-related infrastructure importance.

Vulnerability, on the other hand, is assessed through an Infrastructure Vulnerability Index (IVI) that captures both structural weakness and environmental risk. This index accounts for the condition of bridges—rated from A (good) to D (poor)—along with their relative size and frequency within a road segment. These structural factors are combined with regional hazard exposure levels derived from the INFORM Subnational Risk Index, which provides data on the likelihood and severity of natural disasters such as floods and cyclones across different areas of Bangladesh. Inspired by the methodology of Lu, Xu, and Zhang 2021, this integrated index allows us to identify which road segments are most likely to fail or become impassable during extreme events.

By combining these two dimensions—criticality under normal conditions and vulnerability under stress—we aim to build a comprehensive picture of the transport network's strengths and weaknesses, and to identify where targeted interventions could most effectively improve resilience.

This study seeks to address the following research questions:

1. Which road segments and bridges are most critical to the functioning of the cargo transport network in Bangladesh?

2. Which infrastructure elements are most vulnerable to failure or disruption due to natural hazards?

3. What interventions could most effectively enhance the resilience of the transport network based on combined criticality and vulnerability metrics?

The remainder of this report is structured as follows. Section 2 introduces formal definitions of criticality and vulnerability, along with their theoretical grounding and operationalization for this study. Section 3 describes the methodology used to calculate criticality and vulnerability scores from the RMMS and auxiliary datasets, including data preprocessing steps, the construction of the network, and metric formulations. Section 4 presents the results of the analysis, highlighting the top 10 most critical and most vulnerable roads in Bangladesh based on separate evaluation criteria. Section 5 discusses the findings in a broader context, reflects on the implications for infrastructure planning and policy, and considers the methodological limitations of the analysis. Finally, Section 6 concludes with a summary of insights and recommendations for improving the resilience of the transport network.

2 Definitions

2.1 Criticality

Criticality refers to the economic importance of a road based on the volume of goods transported, which is a function of three key factors: traffic, betweenness centrality, and the percentage of traffic consisting of trucks. In our model, criticality scores are calculated for each road segment (edge) by considering these three factors. The traffic importance is represented by the normalized traffic volume, accounting for how much traffic the road carries. Betweenness centrality measures how crucial the road is in connecting various parts of the network, and the economic importance is captured by the percentage of traffic that consists of trucks, which reflects the direct economic contribution of the road. The criticality score for each road is calculated as the weighted sum of these factors, with traffic importance contributing 0.2 betweenness centrality contributing 0.4, and the truck traffic percentage contributing the remaining 0.4 . This formula is in part based on research on criticality metrics in transport networks B. A. Jafino, Kwakkel, and Verbraeck 2019. They define a large quantity of criticality metrics. In this research, multiple from this list were chosen to define a comprehensive representation of criticality of the Bangladeshi road network. The most important assumption made for this is that economic importance can be effectively represented by the percentage of trucks that drive over a specific road. Considering the limited data this approximation was used. This method is inspired by the methodology in Bramka Arga Jafino 2021, where there is a focus on the freight traffic over the Bangladeshi road network.

2.2 Vulnerability

Vulnerability in the context of the Bangladesh case can be defined as the lack of reliability of the system when exposed to exogenous hazards. As outlined by Berdica 2002, assessing the vulnerability of transport networks primarily facilitates commuting and connectivity as it could show the system's susceptibility to incidents that could substantially diminish the functionality of the road network. It stated that is is important to identify the critical components or locations within the road network and assess the implications of significant damages, often relating it to natural disasters. Moreover, vulnerabilities can also be revealed through technical failures due to the government's or transportation authorities' oversights. Consequently, according to Lu, Xu, and Zhang 2021, the evaluation of the vulnerability of the transport network should also consider the socioeconomic effects that occur when the road network loses its utility. In our model, the idea is to focus on the more vulnerable parts of the network based on knowing which parts are most at risk from hazard. For instance, a failure in one of the bridge would also affect the entire road which disrupts travel and cuts connections to different area, showing how connected and dependent the whole network is on each parts.

3 Methodology

This section explains the methodology for the criticality analysis and the vulnerability analysis.

3.1 Exclusion of Z-Roads from the Analysis

In this study, we focus exclusively on N (National) and R (Regional) roads, while filtering out Z (District) roads. This decision is based on the assumption that Z-roads play a less critical role in the overall transport network of Bangladesh. We'll elaborate on this assumption below.

The primary reason for this choice is that Z-roads generally carry lower traffic volumes and serve local rather than national connectivity. In contrast, N and R roads are the backbone of Bangladesh's transport network, as they are facilitating long-distance travel and economic activity, particularly for freight transport. Since all major bridges and critical infrastructure are part of the N and R road network, disruptions to Z-roads are unlikely to significantly impact nationwide connectivity.

The exclusion of Z-roads is relevant for the policy making, as infrastructure investments and maintenance efforts are typically prioritized for N and R roads. By focusing on these major roads, our analysis aligns more closely with decision-making processes related to national transportation planning.

However, while this approach ensures a strategic national perspective, it does not capture local vulnerabilities that may arise from the disruptions to Z-roads, particularly in rural or disaster-prone areas.

3.2 Criticality Analysis

First construct network from the RMMS data, which is a comprehensive dataset of the Bangladesh road network with traffic data. The data that was used for the following economic analysis. Firstly, we needed to define the economic importance or weights of the data. To determine this, we made the following equation:

$$E = \frac{H + S + M}{T}$$

where:

- H = Traffic Data-Heavy Truck, amount of traffic
- S = Traffic Data-Small Truck, amount of traffic
- M = Traffic Data-Medium Truck, amount of traffic
- T = Total-Total AADT, amount of traffic
- E = Economic weight, presented as a fraction

This methodology is a interpretation of how they find the economic importance of a road in Bramka Arga Jafino 2021. Since the data we have is limited in granularity, the decision was made to represent the economic importance of a road by the described definition.

After this weight was determined. The dataset was made into a networkx graph to further analysis the criticality. This was done by identifying the end and start location of each data entry/road segment with it's geographical location. This was used to identify all links and nodes that should be in the network. Each node was given multiple attributes that would be needed in the analysis later on; segment length, economic weight and total traffic. Then the three criticality metrics were scaled from 0 to 1, This is both to make sure the eventual criticality will be measured in [0,1]. Below there is an example given how this scaling takes place for each of the three metrics. The example is for the betweenness centrality.

$$B'_e = \frac{B_e - \min(B)}{\max(B) - \min(B)}$$

With the following variables:

- B_e is the actual value of the weighted betweenness centrality. e.
- B'_e is scaled value of the betweenness centrality. e.

After this was calculated, the final criticality score was calculated for each road segment with the equation below. The whole dataset was then sorted on this final criticality score and turned into a csv file for further analysis in the Results section of this research.
The final criticality score is computed as:

$$C_e = 0.2T_e + 0.4B'_e + 0.4E_e$$

where:

- C_e is the criticality score of edge e.
- T_e is the scaled traffic importance.
- B'_e is the scaled betweenness centrality.
- E_e is the scaled economic importance.

3.3 Vulnerability Analysis

In identifying the most vulnerable roads, we decomposed the transport network into the type of infrastructure, mainly as road and bridge. As an assumption, we consider the roads to all have the same level of resilience as they share the basic components. However, due to the bridges different conditions in the dataset ('BMMS_overview.xlsx'), we decided that their ability to withstand disruptions will be the main variable in order to find out the entire road's vulnerability.

In our notebook called vulnerability_with_bridges, We wanted to see how well each road could withstand hazards and we used information from a United Nation Bangladesh report (*Bangladesh INFORM Sub-National Risk Index 2022* 2022) to identify how much of a risk each of the natural disaster posed for each road based on their location (zone). We gave each type of disaster a score according to the report range. The higher the hazard index, the higher the risk.

Following the hazard index, we could calculated the Infrastructure Vulnerability Index by defining weights to each of the bridge condition. In this case, we put A as 0.1, B as 0.3, C as 0.6, and D as 1. Meaning, D has the highest weight as its the worst condition. Then, calculating the Infrastructure Vulnerability Index came from a formula that is developed according to the work of Lu, Xu, and Zhang 2021.

$$M = \sum w \cdot \frac{1}{h} \cdot \frac{l_b}{l_{rs}}$$

Noted as M, the Infrastructure Vulnerability Index ranges from 0 to 1, with 0 being the most vulnerable. According to the formula, each bridge will contribute to the index according to a few key factors. The weight (w) assigned to its condition, where poorer conditions like D carry higher weights than better ones like A. Second, the number of bridges (h) along each road section and their corresponding condition scores. And third, the relative length of each bridge (l_b) compared to the total length of the road section (l_{rs}), which helps indicate how critical the bridge is—if it were to fail, that section of road would effectively become unusable.

After identifying the infrastructure vulnerability index, we now calculate the vulnerability score that also derives from the same paper. We take into account the hazard exposure by subtracting the hazard index from 1. This way, the final score reflects both structural weaknesses and environmental risks, giving a more complete picture of which roads are most likely to fail under pressure.

4 Results

4.1 Criticality

To start getting the final results for the most critical roads, we first map a choropleth on the criticality score of N and R roads in Bangladesh as shown in the figure below to see a general overview of the results from our data analysis as well as the distribution of the criticality scores. The distribution of criticality is right-skewed meaning not many segments has are highly critical.

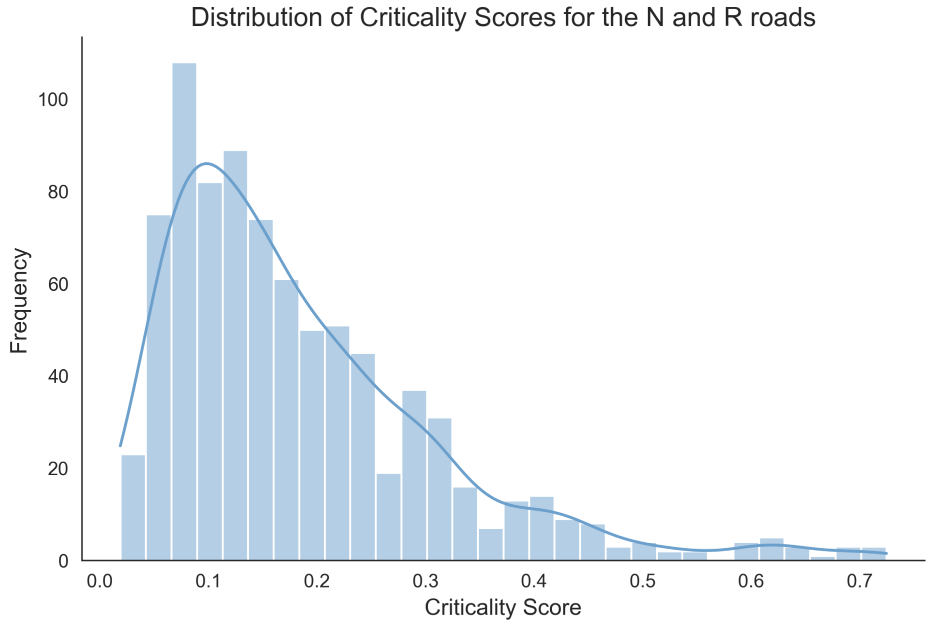

Figure 1: Distribution of Criticality Scores for the N and R Roads

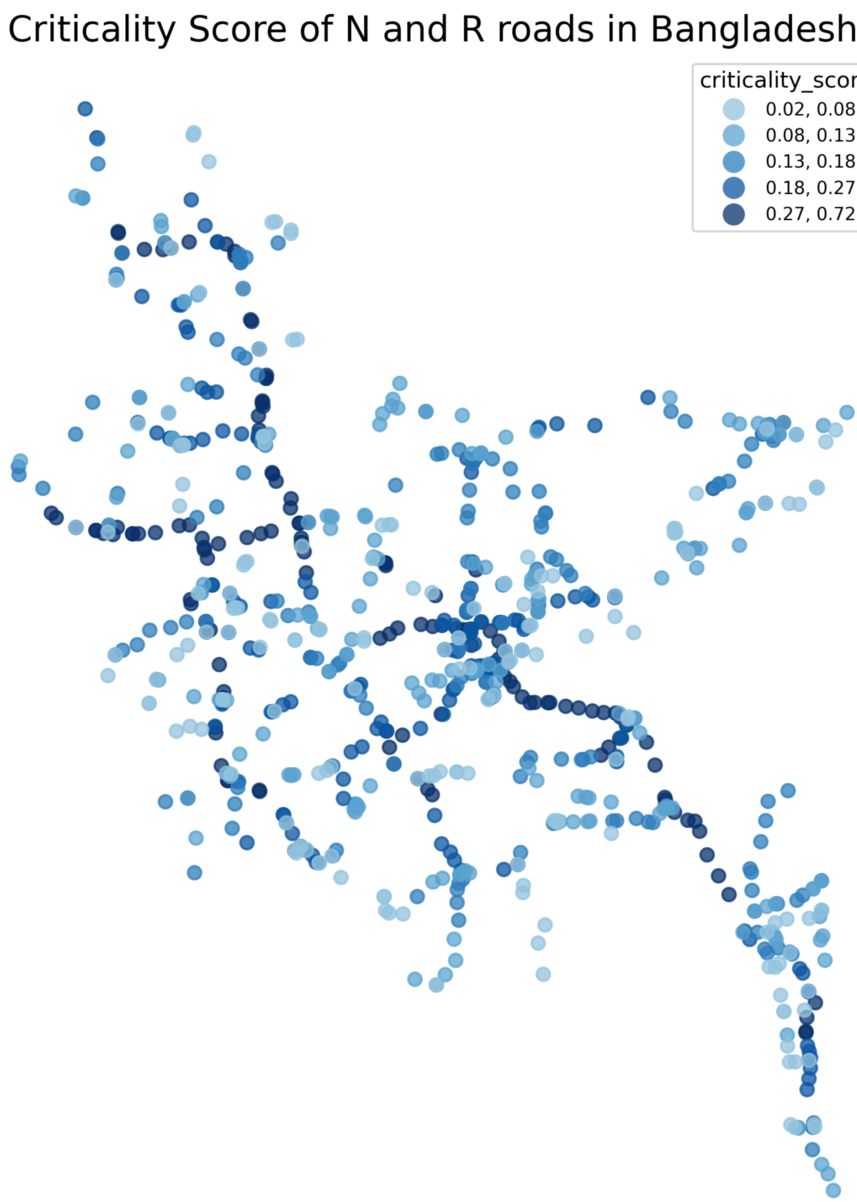

Figure 2: Criticality Score of N and R roads in Bangladesh

To identify the most critical roads, the criticality score were used and aggregated per road. The following metrics were considered: (1) mean criticality score per road to understand the general idea of how critical a road is on average, (2) maximum criticality score per road to see the most critical segment of each road, (3) standard deviation of criticality score to indicate the variability in criticality along the same road as high value suggest uneven distribution, (4) traffic influence on criticality to compare total_traffic and criticality_score to reveal heavily used roads which are also critical. By doing so, we hoped to see that roads with high mean and high max criticality to be consistently critical, roads with low mean but high max criticality may have localized bottlenecks or weak points, and roads with high variability may indicate areas where targeted interventions (e.g., lane expansions, alternative routes) are needed. After examining the results, we decided to rely on the mean vulnerability. As criticality is about understanding how important a segment is to the overall function of the network, not just how likely it is to fail. Unlike vulnerability that will be explained in the next subsection, criticality, ranked using the average, allows us to reflect the typical load or influence a segment has which gives a more balanced picture of its ongoing operational role rather than its performance in extreme cases.

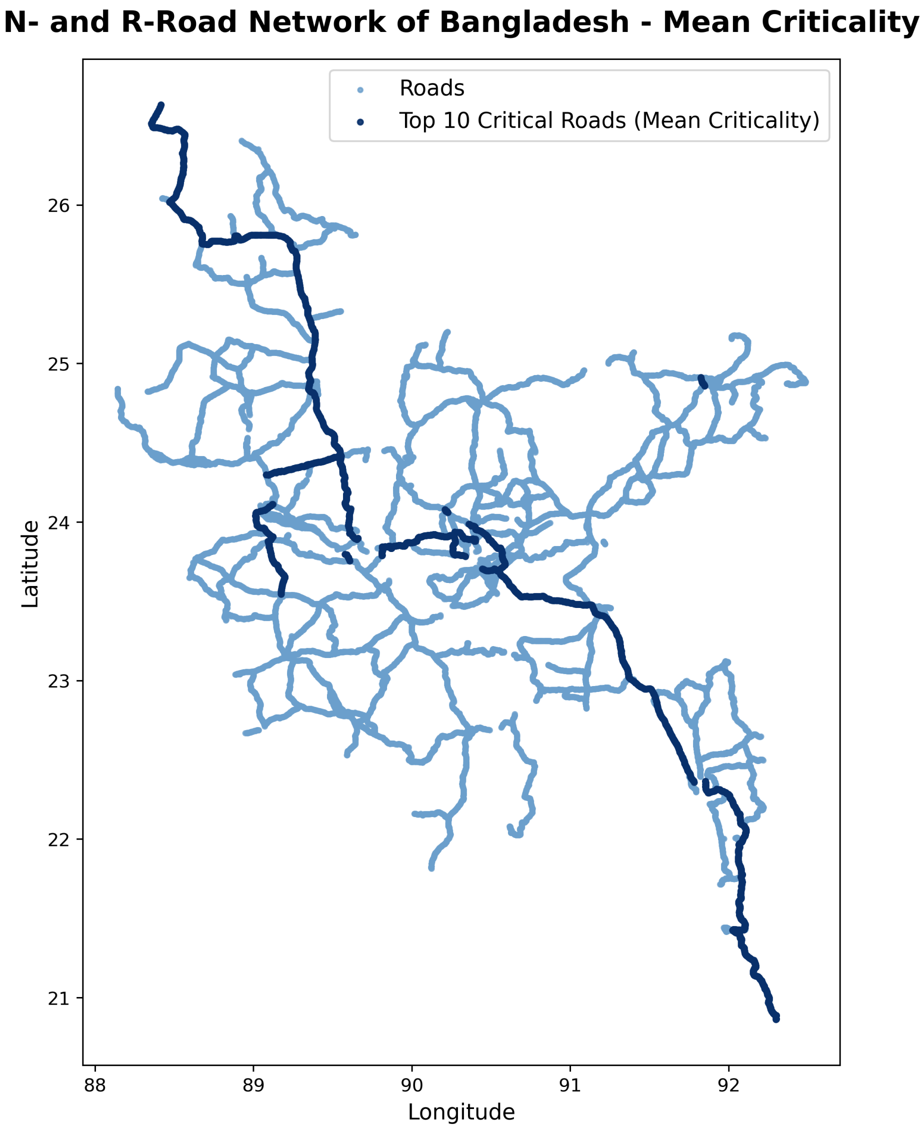

Figure 3: N- and R- road network of Bangladesh. The top 10 most critical roads (based on average (mean) vulnerability per road) are displayed in dark blue.

The figure above shows the top 10 critical roads of Bangladesh while the figure below presents a clear overview of the Top 10 critical roads.

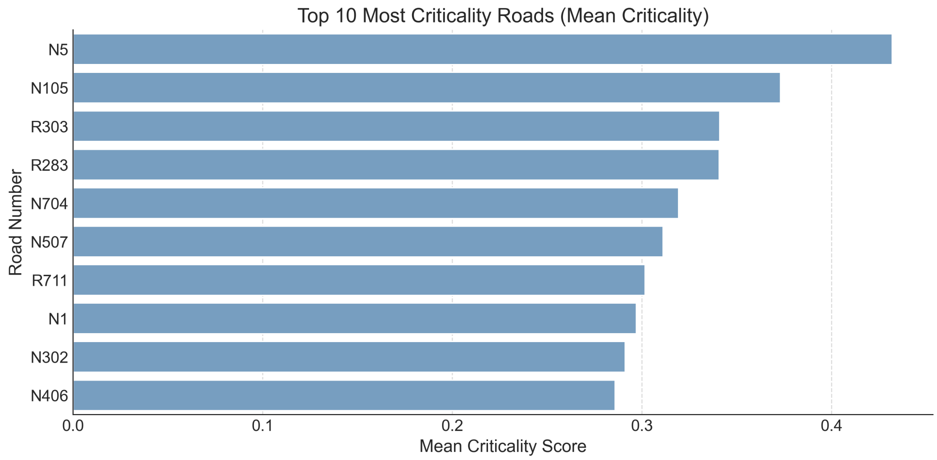

Figure 4: Top 10 Critical Roads

Additionally, we added the figure below of the different critical N and R roads in Bangladesh to give a general idea of the whole transport network.

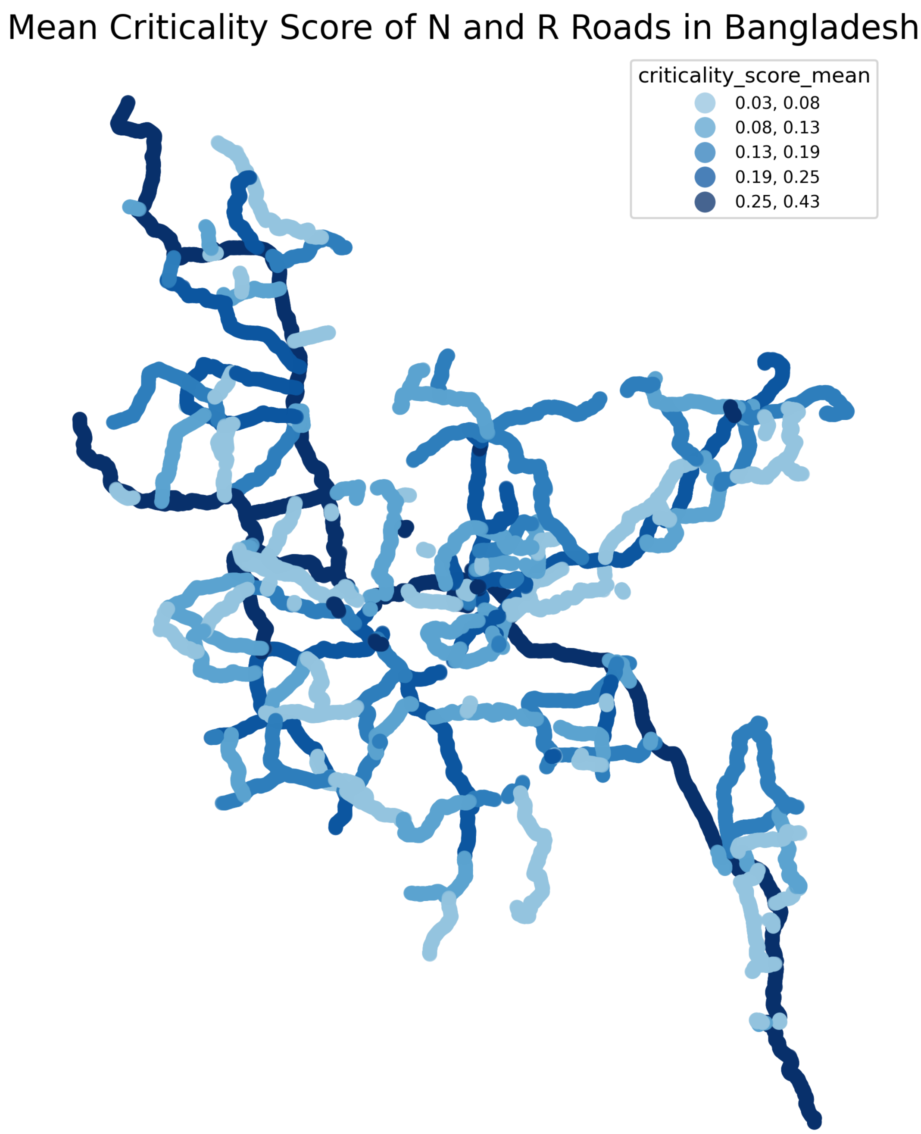

Figure 5: Mean Criticality Score of N and R roads in Bangladesh

4.2 Vulnerability

In order to get the final results, the step-by-step is that we first map a choropleth map of the vulnerability score of N and R roads in Bangladesh to get a general view of the results as well as the distribution of the scores. The distribution of the vulnerability score is also highly right-skewed suggesting that most of the roads are relatively vulnerable, mainly due to the hazard levels and low bridge conditions.

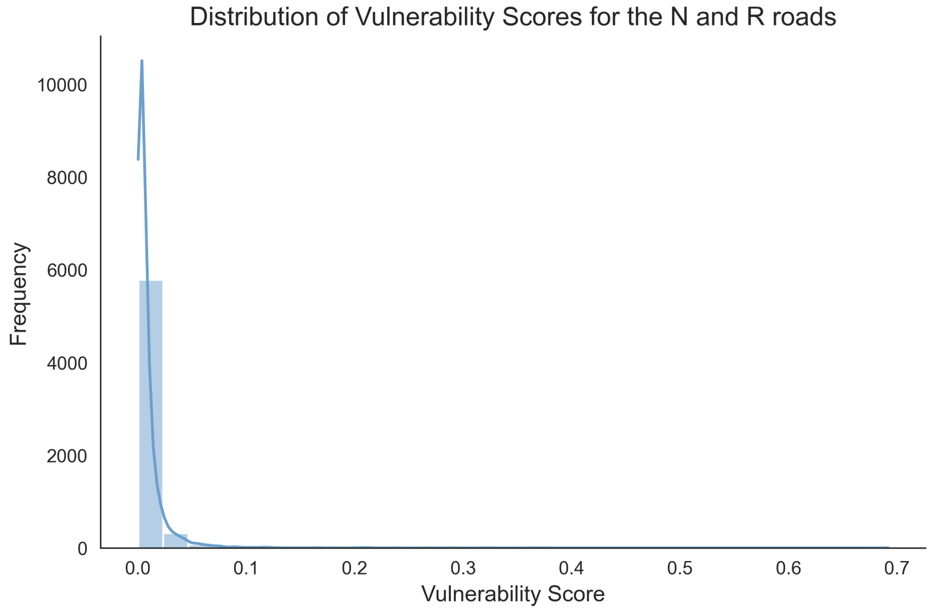

Figure 6: Distribution of Vulnerability Scores for the N and R Roads of Bangladesh

Figure 7: Vulnerability of the N- and R-road network of Bangladesh

The summary statistics of the Vulnerability Score were used and aggregated per road. By doing so, we were able to get the top 10 most vulnerable roads relying on the maximum vulnerability score instead of the mean. This is important because even if the average vulnerability is low, a single highly vulnerable segment can become an highly important point of failure, especially during extreme hazardous events. In this case, it would be the natural disasters of infrastructure collapse. Using the maximum highlights important sport that demand immediate attention and supports a risk-averse approach to decision-making. In short, using maximum values are more sensitive to outliers which aligns with out goals of trying to pinpoint and address the weakest links in the road network system.

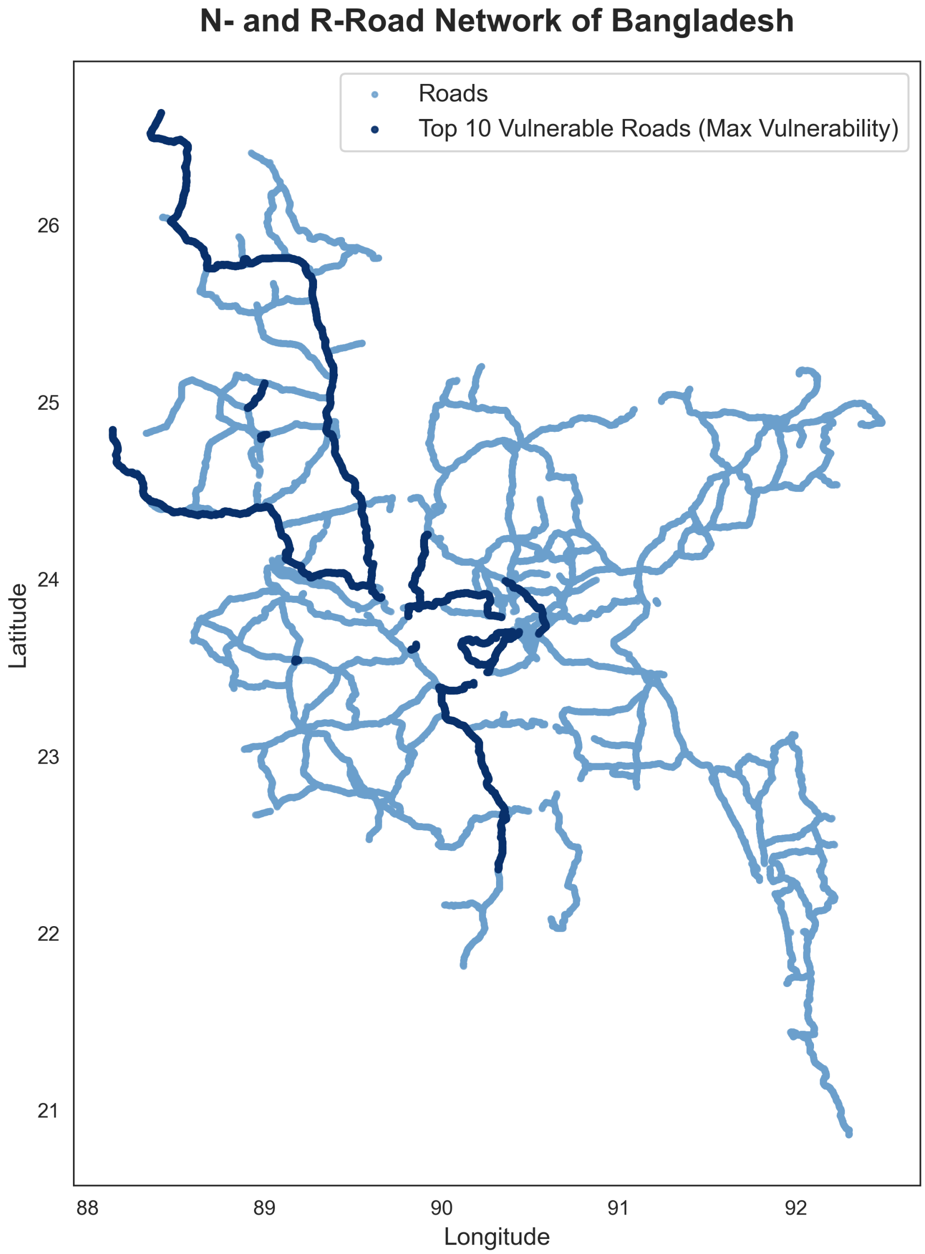

Figure 8: N- and R- road network of Bangladesh. The top 10 most vulnerable roads (based on maximum vulnerability per road) are displayed in dark blue.

The figure above shows the top 10 vulnerable roads of Bangladesh while the figure below presents a clear overview of the Top 10 Vulnerable roads.

Figure 9: Top 10 Vulnerable Roads displayed as a barplot.

Furthermore, we added the following figure of the different vulnerable N and R roads in Bangladesh to give a general idea of the whole transport network.

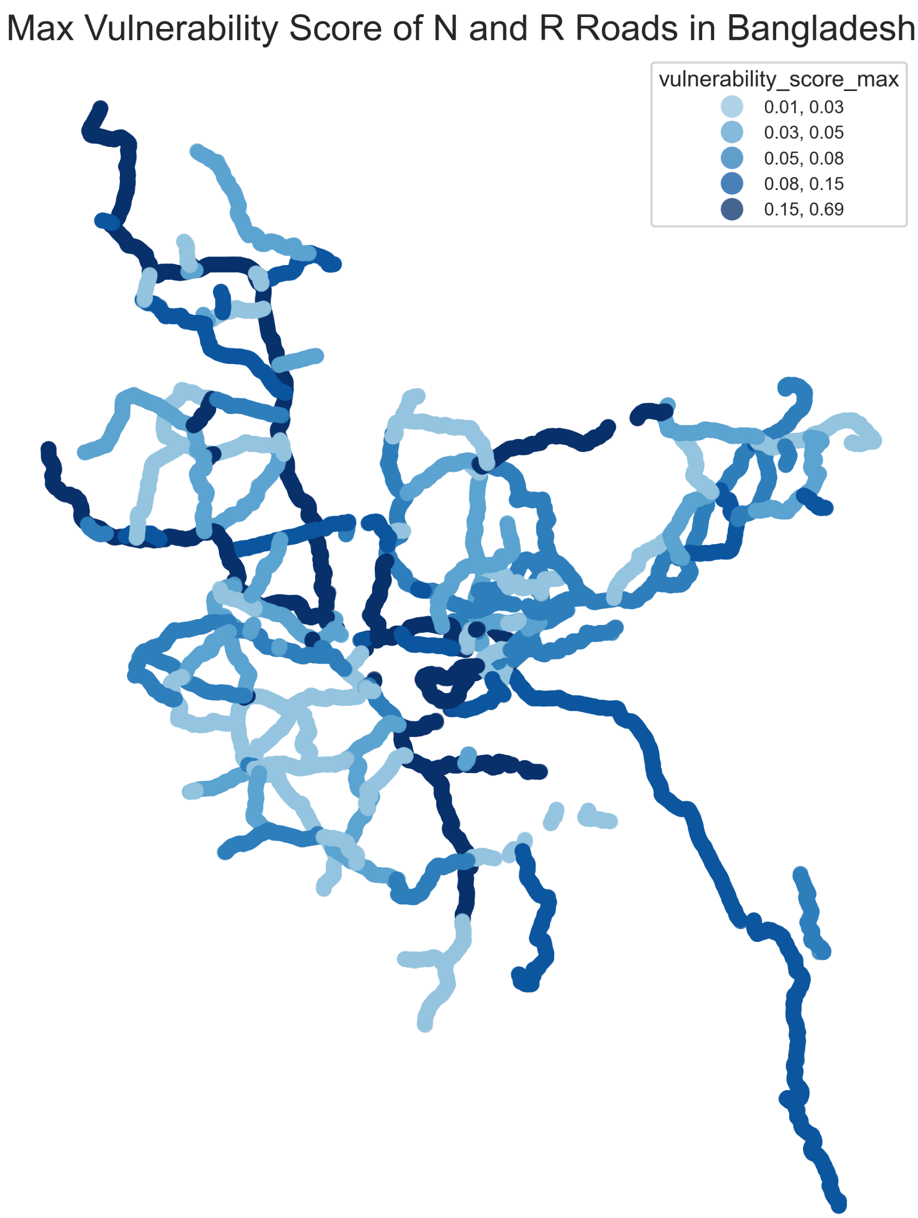

Figure 10: Max Vulnerability Score of N and R roads in Bangladesh

5 Discussion

The analysis of the Bangladeshi road network reveals an interesting relationship between criticality and vulnerability. While some of the roads rank highly in both dimensions, others exhibit a stark contrast—either being highly critical but relatively resilient, or highly vulnerable but less crucial for economic activity. This distinction is crucial for infrastructure planning and prioritization.

At the same moment, we observe an interesting and stark contrast between the use of the parameter maximum vulnerability (based on the maximum vulnerability value of each road) and mean vulnerability (based on the mean vulnerability value of each road), as for maximum criticality and mean criticality. Especially for vulnerability, we observe a stark contrast between the two definitions.

Implications for Policy and Infrastructure Planning

The ranking of roads by criticality suggests that policymakers should prioritize maintenance and expansion efforts on the most economically vital routes. However, the vulnerability analysis highlights that some roads are particularly susceptible to failure due to natural hazards and deteriorating infrastructure. This calls for a balanced strategy that integrates economic importance with resilience measures. Observably, there are two roads which are both in the vulnerability top 10 and the criticality top 10: the N105 and N5. We could argue that, for policymakers should take these two roads for serious when creating an infrastructure strategy.

Limitations and Areas for Improvement

‘ Several assumptions and methodological choices may influence the results. First, the calculation of criticality relies on the assumption that truck traffic percentage is a strong proxy for economic importance. While this is reasonable given the available data, additional socioeconomic factors—such as regional GDP contribution or industrial activity—could further refine the metric. In addition, the criticality definition is based upon three key factors:

1. **Traffic Importance (20%)** – The total traffic volume on a given road segment, normalized for comparison.
2. **Betweenness Centrality (40%)** – A measure of how crucial a road segment is in connecting different parts of the network.
3. **Economic Importance (40%)** – A normalized measure reflecting the direct economic weight of the road.

This approach ensures that roads critical for connectivity (high betweenness) and economic activity (high economic weight) receive appropriate attention. However, it is based upon weighting assumptions. A more empirical approach, using economic and transport impact assessments, could refine these weights.

Second, the edge-betweenness centrality metric assumes that all shortest paths are equally important. However, real-world routing decisions are influenced by additional factors, such as congestion and road quality. Incorporating real traffic flow simulations would improve accuracy.

Third, we've made the assumption that Z (District) roads due to their lower traffic volumes and limited role in national connectivity, could be excluded from the analysis. While we do have good reasons for doing so, it does not capture local vulnerabilities. For future research, it could be an interesting addition to add the Z-roads in the analysis.

Lastly, data availability. We base our data on a dataset which is 95% filtered and cleaned. As always, a better and cleaner dataset leads to better results.

6 Conclusion

This study set out to evaluate the criticality and vulnerability of Bangladesh's national (N) and regional (R) roads, with a specific focus on freight transport. By leveraging traffic data, structural bridge conditions, and regional hazard exposure, we developed a dual-metric framework that helps identify both the most economically important and the most at-risk road segments across the network.

The criticality analysis revealed that a small number of roads play a disproportionately important role in supporting economic activity. These roads exhibit high traffic volumes, centrality in the network, and a high proportion of truck usage. Similarly, the vulnerability analysis showed that most roads are stand out structurally weak and highly exposed to natural hazards. Notably, the use of the maximum value to rank vulnerability—rather than the mean—helped surface key hotspots that might otherwise be hidden in an average-based approach.

By comparing the outcomes of both analyses, we identified segments that are not only critical but also highly vulnerable. These segments, such as the N5 and N105 roads, represent strategic intervention points where targeted investment could significantly improve the overall resilience and functionality of the transport network.

Our methodology, while grounded in existing literature, relies on assumptions due to data limitations. Still, it provides a practical starting point for transport planners and policymakers seeking to enhance the robustness of Bangladesh's road infrastructure.

Future work could improve this analysis by incorporating more granular economic indicators, expanding the dataset to include Z-roads, and simulating real-world traffic dynamics. Despite these limitations, the findings of this report offer actionable insights for building a more reliable and resilient road transport system in Bangladesh.

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7 Appendix A: Acknowledgement

7.1 AI Statement

In accordance with the guiding principles for the responsible use of AI tools, as outlined by TU Delft, the use of generative AI tools such as ChatGPT in this analysis has been conducted responsibly and, hereby, transparently.

AI was used to get the model to do what we wanted. This meant that the ChatGPT was used to generate functions which could be applied on the code. It was checked whether the suggested function by ChatGPT resulted in the behaviour that we wanted to see according to our own mental models. Specifically in debugging, ChatGPT was valuable, as this software could direct us to the bugs present in our software.

7.2 Task Division

Table 1: Distribution of the Workload

Student	**Task**
Ameera	Vulnerability definition, vulnerability code, report writing
Nils	converting RMMS data, data plotting, report writing
William	Vulnerability, report writing
Tobias	Criticality, definition and analysis, report writing
Berend	Criticality, definition and analysis, report writing