Report Assignment 4

Bangladesh Transport Network

A Geospatial Data Analysis Approach

EPA1352: Advanced Simulation

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How many tuk-tuks could a tuk-tuk tuk if a tuk-tuk could tuk tuk-tuks?

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1. Introduction

Bangladesh is one of the most vulnerable countries to natural phenomena due to its geographic location and high population density. The Padma and Brahmaputra rivers split the country into three parts causing livelihood and economy to rely heavily on its transport infrastructure with a focus on bridges. Some bridges are up to 6 km long and can act as a bottleneck in the transport network.

In 2018, the World Bank requested an assessment to identify investment priorities to reinforce bridges in Bangladesh to minimize economic loss under a wide range of natural hazard scenarios (World Bank, 2018). TU Delft developed the BangladeshModel to guide the decision-making process of the World Bank by estimating bridge criticality. This report extends the traditional simulation methodology by utilizing a data analysis approach, studying empirical traffic, flood risk and infrastructure data to inform our understanding about the system at hand.

The data analysis will follow a systematic schemata that aims at identifying the critical and vulnerable infrastructure segments of the Bangladesh transport network to finally assess the most important segments. Hence we ask:

> **(Q1)** Which infrastructure segments have the highest socio-economic criticality in regard to the transport of goods?
>
> **(Q2)** Which segments contribute most to the vulnerability of the multimodal transport network when exposed to natural hazards?
>
> **(Q3)** Based on both criticality and vulnerability, which are the most important infrastructure segments in the multimodal transport network of Bangladesh?

The overall aim is to provide a more holistic understanding of the whole infrastructure network; and thus suggests a framework, guiding the identification of the most important transport segments that have to be improved to ultimately ensure a more efficient, robust and resilient transport infrastructure in Bangladesh.

In analyzing infrastructural segments, this paper pays a larger emphasis on the assessment of road segments for criticality and vulnerability since the behavior of the transportation network is largely driven by road structure. The assessment of bridges will be inherited from the assessment of road segments as it provides the necessary context for the bridge.

2 Criticality and Vulnerability Framework

Transportation networks form the backbone of a nation's economy, and as such, it is crucial to develop and maintain efficient, robust, and resilient infrastructure. There are numerous metrics available for assessing the performance of these networks, but selecting the appropriate metric largely depends on the specific purpose of the analysis. Furthermore, introduced metrics are prone to subjective bias on how to rate different factors (Ukkusuri & Yushimito, 2009). In order to address this issue, Jafino et al. (2020) introduced a three-dimensional framework for infrastructure metrics, which encompasses the level of functionality, ethical considerations, and aggregation methods. By classifying our chosen metrics according to this framework, we can ensure a more comprehensive and targeted evaluation of transport networks.

The argument for why this report focuses on road segments as opposed to predefined roads (e.g. N205) is as followed:

- **Network Reasons:** In studying the transport network, the structural qualities of the road segment is more crucial to the transportation functions as opposed to the highway codes (of the whole road). Hence, studying on the segment level will definitely reveal richer patterns.

- **Statistical Reasons:** It is better to study data with a lower spatial aggregation to prevent statistical bias from Modifiable Areal Unit Problem (Openshaw, 1984), which when aggregated by spatial partitions (i.e. predefined roads) distorts values. For instance, there could be an extremely critical bridge on the N1, but it might not be noticeable if it was aggregated to the N1 level.

- **Practical reasons:** Assessments on the segment level is practical for prescription - especially when a single road could be hundreds of kilometers, understanding critical/vulnerable segments will help in focusing resources efficiently in manageable areas. Increases feasibility of policy intervention/implementation

2.1 Criticality

Transport criticality is a key transport metric that measures the impact of a particular transport segment within a transportation network. However, one has to acknowledge that most decision frameworks are limited to a specific use case (Ukkusuri & Yushimito, 2009). For our purpose, we take an economic critical approach and therefore assess transport criticality by calculating the average tons of goods transported via that specific segment. This way, valuable insights of the economic significance of each road segment are gained. To classify this metric according to the three dimensions by Jafino et al. (2020), the metric takes a connectivity-focused approach in the functionality dimension, a utilitarian perspective in the ethical dimension, and a local approach in the aggregation dimension (Figure1).

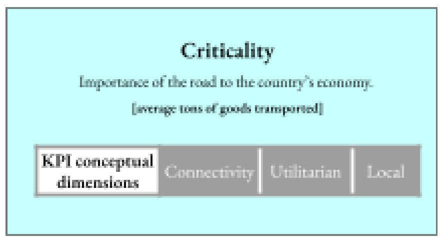

Figure 1. Summary of the Criticality Index Average Tons of Goods Transported

It is important to note that the metric we have defined is only one approach to assessing criticality in transportation networks; there are numerous other metrics that capture criticality from different perspectives. For instance, social criticality could be another approach that focuses on the number of people traveling through a particular transport segment, rather than the economic value represented by the tons of goods transported. Such metrics would prioritize the importance of transportation infrastructure based on its impact on society and the movement of people, thus providing a more human-centric analysis.

In order to calculate the average tons of goods transported via a specific segment, we make use of the Annual Average Daily Traffic (AADT) that is included for each vehicle type and road segment in the RMMS dataset. AADT is the standard measurement for vehicle traffic load on a section of road, and the basis for decisions regarding transport planning, or to the environmental hazards of pollution related to road transport (Davis, 1997). The mathematical representation of AADT is:

$$AADT = \sum_{i=1}^{365} V(i) \cdot \frac{1}{365}$$

Where: V(i) = vehicle volume for day i.

This formula means that we sum up the vehicle volume for each day of the year to get the total vehicle volume for the year. Afterwards, we divide the result by 365 to get the average daily traffic for the year.

In order to get the average tons of goods transported via a specific segment, we first need to have data on the average tons of goods per vehicle type. Information about the different vehicle types was found in a report by the Ministry of Road Transport and Bridges (2016, p. 6-1) of Bangladesh. In another report by the ministry (2017) representative models of the vehicle types are provided (Table A1).

Table 1. Surveyed Vehicle Type (Ministry of Road Transport and Bridges, 2016, p. 6-1)

Survey Type	Vehicle code	Vehicle type
T/C Only	①	Motorbike
	②	CNG (Auto-rickshaw)/Baby taxi
T/C + O/D	③	Passenger car (Sedan, SUV), Taxi
	④	Micro bus (up to 15 seats)
	⑤	Medium bus (16-39 seats)
	⑥	Large bus (40 seats or more)
	⑦	Small truck (2 axles, less than 3 tons)
	⑧	Medium truck (2 axles, over 3 tons)
	⑨	Large truck (3 axles or more)
	⑩	Trailer truck
	⑪	Utility (Jeep, Pickup, Legna)
T/C Only	⑫	Bicycle
	⑬	Cycle rickshaw
	⑭	Others

In a freight survey the weight of the average consignment in tonnes (AC) was collected for the small, medium, and large trucks (Table A2). Only those vehicle types are considered freight traffic. For other vehicle types, there is no data on the weight of the average consignment in tonnes. However, there is data on the Unloaded Weight (UW) and Gross Vehicle Weight (GVW) for each vehicle type (Table A3). This can be used to arrive at a reliable weight of the average consignment in tonnes. We do this by taking the halve of the difference between UW and GVW. This is done because we assume that on average a vehicle is on average half full. Then it is rounded to two decimal places. The final data used is presented below.

Table 2. Weight of the Average Consignment in Tonnes per Vehicle Type

Vehicle type	Vehicle code	Weight of the average consignment in tonnes (AC)
Motorcycle	1	0.04
Auto rickshaw	2	0.17
Car	3	0.19
Micro Bus	4	0.53
Medium Bus	5	2.85
Large Bus	6	4.90
Small Truck	7	5.00
Medium Truck	8	14.0
Heavy Truck	9	28.0
Utility	10	0.31
Cycle Rickshaw	11	0.10
Bicycle	12	0.02
Cart	13	0.15

With these numbers, it is possible to calculate the criticality index, which we use to assess the criticality of road segments. The criticality index is defined as the weighted total tons transported per day for each road segment. The value is weighted with the average tonnage of the main roads, as this puts the individual road segments in relation with the criticality of the total network. For this we need for each road segment the AADT per vehicle type and the average load capacity for each vehicle type.

The mathematical representation is:

$$Criticality\ index(j) = \frac{\sum_{i=1}^{n} AADT(i,j) \cdot LC(i)}{m}$$

Where:

m: average tons transported by main road
n: types of vehicles
j: road segment
LC(i): average load capacity in tons for vehicle type 'i'.

2.2 Vulnerability

Vulnerability has many definitions depending on the specific approach and sector. Bangladesh transport network is already threatened by flooding. Climate change scenarios suggest an increase in these risks (Department of Environment, 2012 & World Bank, 2023). State of the art approaches to road design and management increasingly consider climate change as it has the potential to affect road safety and performance (e.g. Natural Resources Canada, Climate Corporation, Deltares' RoadAdapt, and ISO14090). Implementing an in-depth vulnerability assessment considering climate change scenarios and methodologies is outside the scope of this analysis. Nonetheless, the vulnerability definition of these frameworks was utilized in this report to enable future in-depth assessments that do include climate change. Thus, vulnerability is defined with the following three components (Figure 2):

- **Exposure**: Extent to which a road link is subject to face flooding. This indicator was calculated using a dataset of historical excess flooding measured by hydrometric stations and reported by the FFWC (2022).
- **Sensitivity:** Extent to which flooding could affect a road segment. This indicator was calculated using the condition category from the RMMS dataset.
- **Adaptive capacity:** Accessibility of actions to reduce risks. This indicator was calculated using bridge length from the RMMS dataset. It is assumed that local governments are more likely to have the capacity to repair and ameliorate short bridges but longer bridges could further benefit from external support such as World Bank expertise and financial support. Thus longer bridges have less adaptive capacity represented by a higher value in the indicator.

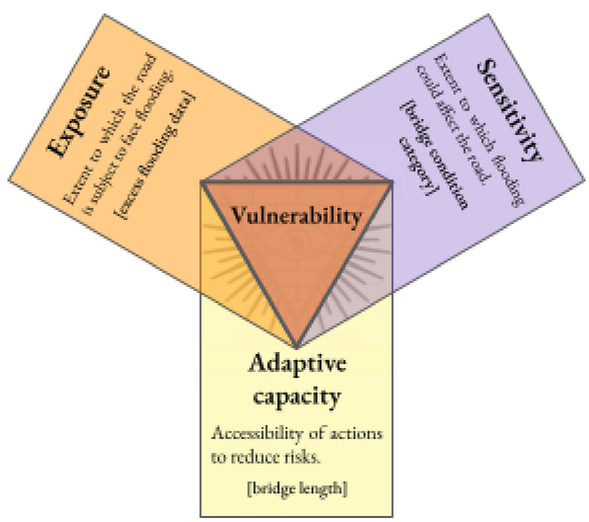

Figure 2. Indicators of Vulnerability: Exposure, Sensitivity and Adaptive Capacity (Rowan et al., 2014)

The indicators for vulnerability were calculated using the equations mentioned in Table 3. For sensitivity and adaptive capacity, weighted sums were performed. The weights were estimated using an exponential relation that illustrates the fact that risk does not usually increase linearly (Comes & Copeland, 2020). We assume that the increase in the sensitivity of a bridge A to a bridge B is smaller than from a bridge C to a D. For adaptive capacity we assume that the difficulty of intervening in a bridge grows exponentially with bridge length. As an illustration of this relation, the adaptive capacity of a section with one 1,800 m bridge would be 1 whereas a section with four 450 m bridges would have a smaller adaptive capacity of 0.76 (Appendix B).

To define the specific value of the progression factor of the exponential relation a calibration process with measured or synthetic data, as well as a sensitivity analysis to different values are usually performed (Erath, 2011). The progression factor, also known as the base, is usually between 1 and 2 where 2 generates a more aggressive relation. In this report, a progression factor of 1.2 was defined which is inline with risk assessment literature (Appendix B). Nonetheless, further analysis to refine the progression factor would be advisable to reduce this source of epistemic uncertainty.

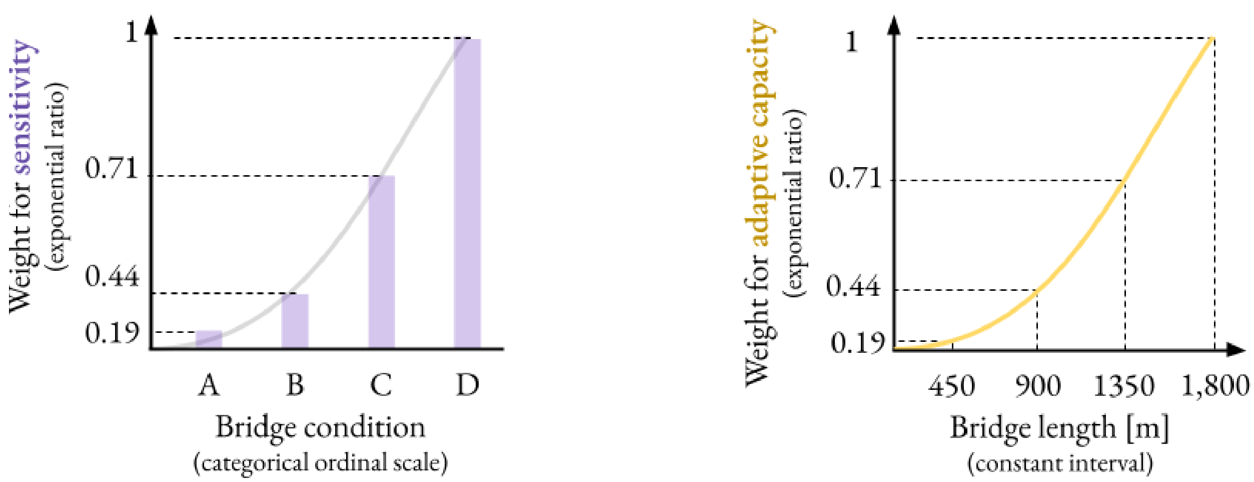

Figure 3. Illustration of Weight Estimation for the Weighted Sum Equations of Vulnerability Indicators Using an Exponential Relation with a 1.2 Progression Factor

All three indicators were calculated using the equations described in Table 3. The LRPs in the RMMS dataset are placed somewhat arbitrarily making the length road segments highly variable. For this reason, exposure and sensitivity are divided by bridge length to avoid skewing the results towards the longest links.

Table 3. Detailed Equations of the Indicators for the Vulnerability Index

Indicator	Equation
Exposure	$Excess\ Water\ Level = Highest\ Water\ Level - Danger\ Level$ **Where:** **Highest Water Level**: Water Level during Flood Event **Danger Level**: Maximum Water Level
Sensitivity	$\frac{Bridges_A \omega_A + [...] + Bridges_D \omega_D}{LinkLength_m}$ **Where:** **m:** bridge segment **Bridges**: number of bridges of each category in the road segment. **ω** : weights used in the sum that were calculated using a progression factor of 1.2 and are D:1, C:0.71, B:0.44 and A:0.19
Adaptive capacity	$\sum_{n=0}^{n} \left(\frac{BridgeLength_n}{max\ BridgeLength}\right)^{pf} / LinkLength_m$ **Where:** **m:** bridge segment **n:** number of bridges in the road segment. **pf**: progression factor representing the exponential decrease in adaptation capacity with bridge length. The value is set to 1.2 for this report. **Max Bridgelength**: the maximum bridge length in the whole network.

The results of the indicators are then normalized using a min-max normalization. This process enables the integration of the three indicators into a single vulnerability index using a geometric average. Other methods such as principal component analysis (Kris & D'Errico, 2022) or weighted average using data or expert-based paired comparisons using qualitative-quantitative methods and software (Floridi & Lauderdale, 2022) could also be used in future works.

2.3 Importance: Index Synthesis

To combine both transport network metrics into one final KPI, we utilize an overlap analysis, introducing the concept of importance in transportation networks as an amalgamation of the two key indices: criticality and vulnerability (Figure 4). To do so, we computed the average sum of segment criticality and vulnerability. By considering both aspects, we are able to identify road segments that are not only of high economic significance, but also face potential risks or disruptions.

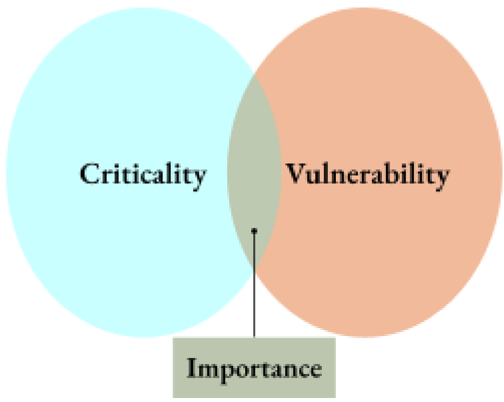

Figure 4. Venn Diagram to Illustrate the Relationship Between Vulnerability, Criticality and Importance

This method allows for effective prioritization of infrastructure investments and maintenance efforts. In addition, incorporating both; criticality and vulnerability in the analysis ensures a more comprehensive understanding of the segments that warrant attention, as they play a crucial role in the functioning of the network and exhibit increased susceptibility to challenges or disruptions. This approach aligns with the overall objective of optimizing resource allocation and enhancing the performance of the transportation infrastructure. ultimately leading to improved resilience and efficiency within the transportation system.

3 Implementation

3.1 Overview on Data

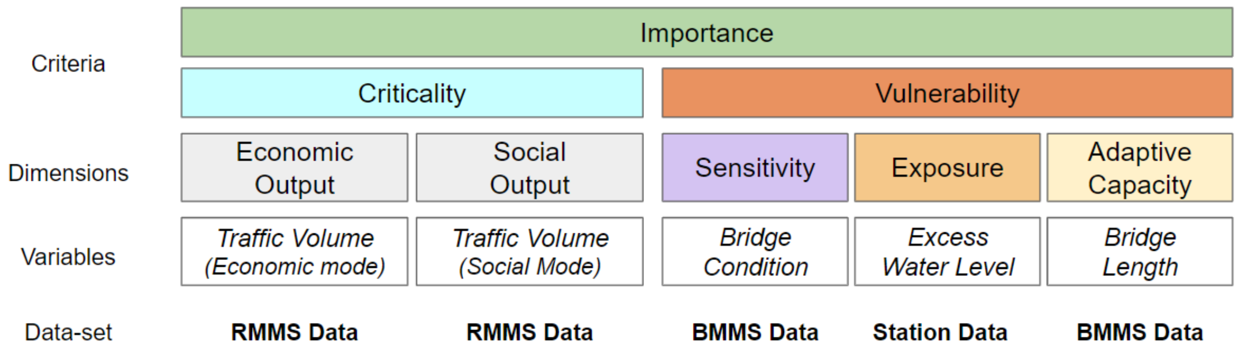

Figure 5. Overview of Criterias, Variables and Data Source

In our methodology section, the additional data processing required for analysis will be described. Figure 5 covers the necessary indicators needed for the assessment and the data source. Essentially, a cohesive dataset should be the goal: a road dataset as a line geodataframe with *Traffic Volume* and *Excess Water level* per road segment, a bridge dataset with *Bridge Condition* and *Bridge Length*.

- In section 3.1, the focus will be on producing a clean line geodataframe.
- In section 3.2, the will focus be on joining (spatially) water exposure from station data to the road segments

3.1 Data Preparation

1 Filter to only Main Roads

The first step was to select only the main roads from the dataset. This was done by filtering the dataset to include only N roads, which were justified as main roads based on a set of predefined criteria.

2 Removed all with only one road segment entry or no traffic data

Next, we removed all roads that had only one entry in the dataset. These roads were removed to improve the overall quality of the dataset. We also removed all roads that had missing traffic data. These entries were removed because they could not be used in the analysis, and their inclusion could introduce errors into the analysis.

3 Linestring

The Start and End LRPs were cross-referenced in the LRP datasource of the *_roads3.csv* and then connected with a linestring to enable geospatial visualizations.

3.2 Extraction of Flood Exposure Data

1 Extracting water station data, choosing metrics

The data source used was the recorded water levels at water stations during the 2017 Bangladesh floods (FFWC Bangladesh, 2023) . It records the location (lon, lat) of water stations as well as flood-related data (cms) i.e. water level, highest water level, and danger level. Flood exposure can be approximated at each road with an additional indicator "excess water level" created based on the difference between highest flood level and danger level (threshold height for warnings). If the highest flood level is not required, the water level will be used instead.

2 Get centroid of road segments

In order to simplify the geometry of the road data, each road segment is converted into a single point (centroid of line) based on the LRP start and end coordinates.

3 Spatial join road segments to water stations through nearest neighbor method

The road segment points were compared with the water station coordinates using the nearest neighbor method (searching for the closest point). A full spatial join was completed where the flood-related data was added to the road data. Other options of spatial joins considered involve taking averages, max or min, but all of these involve the assumption of a search radius. According to Occam's razor, the simplest explanation should be preferred over the more complex ones - hence, the other options will not be used.

4 Exploratory Data Analysis

Exploratory data analysis (EDA) is a crucial first step to fully understand and interpret the provided data sets.. In the context of traffic data in Bangladesh, EDA can help us gain insights into the traffic flow, identify traffic hotspots, and understand the impact of traffic. With Bangladesh being one of the most densely populated countries in the world, traffic congestion has become a significant problem in its urban areas, leading to increased travel times, air pollution, and road accidents. By conducting EDA on traffic data in Bangladesh, we can better understand what road segments and roads have the highest traffic volumes, and what modes of transport are the most relevant.

4.1 Modes of Transport

Average Traffic Volume per Mode of Transport

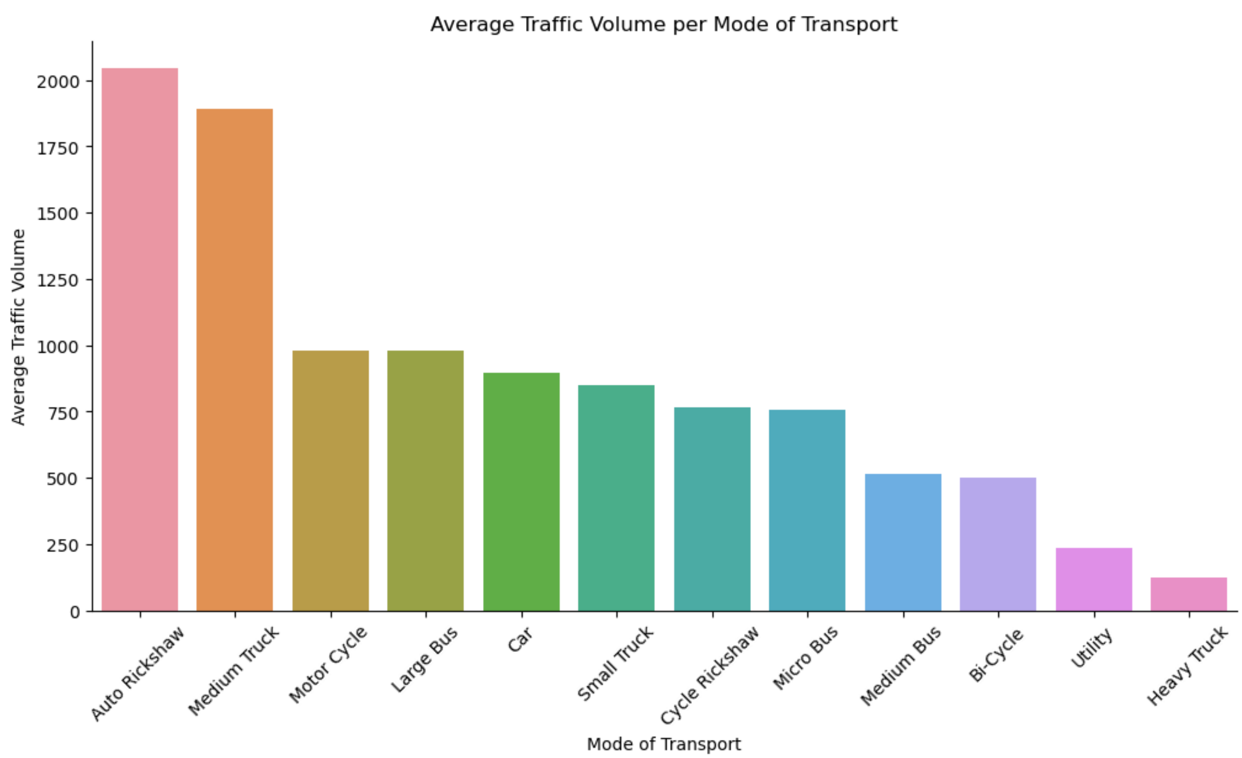

Figure 6. Bar Graph of Average Traffic Volume per Mode of Transport

Based on the data presented (Figure 6), it is clear that auto rickshaws are the most widely used mode of transport in the country. This is likely due to the fact that auto rickshaws are a relatively inexpensive and convenient means of transportation, especially for short trips within cities.

Medium trucks are the second most commonly used mode of transport, likely due to their versatility and ability to transport goods across relatively long distances. Heavy trucks, on the other hand, appear to be the least commonly used mode of transport in Bangladesh. This may be due to the fact that heavy trucks are typically more expensive to operate and maintain than other modes of transport, and are therefore used primarily for long-distance transportation of goods.

In the context of the Bangladesh transport network, these findings suggest that the country's transportation infrastructure is best suited for relatively short-distance travel within urban areas. This is consistent with the fact that auto rickshaws are the most commonly used mode of transport in Bangladesh, as these vehicles are well-suited for navigating the congested and often narrow streets of cities and towns.

Additionally, the high usage of medium trucks suggests that there is a significant demand for the transportation of goods across relatively short distances within the country. However, the low usage of heavy trucks indicates that long-distance transportation of goods may not be as common or cost-effective in Bangladesh. Heavy trucks might also not be as suitable as they require larger streets in better condition and are less versatile in case of disruptions.

Correlation Matrix of Modes of Transport

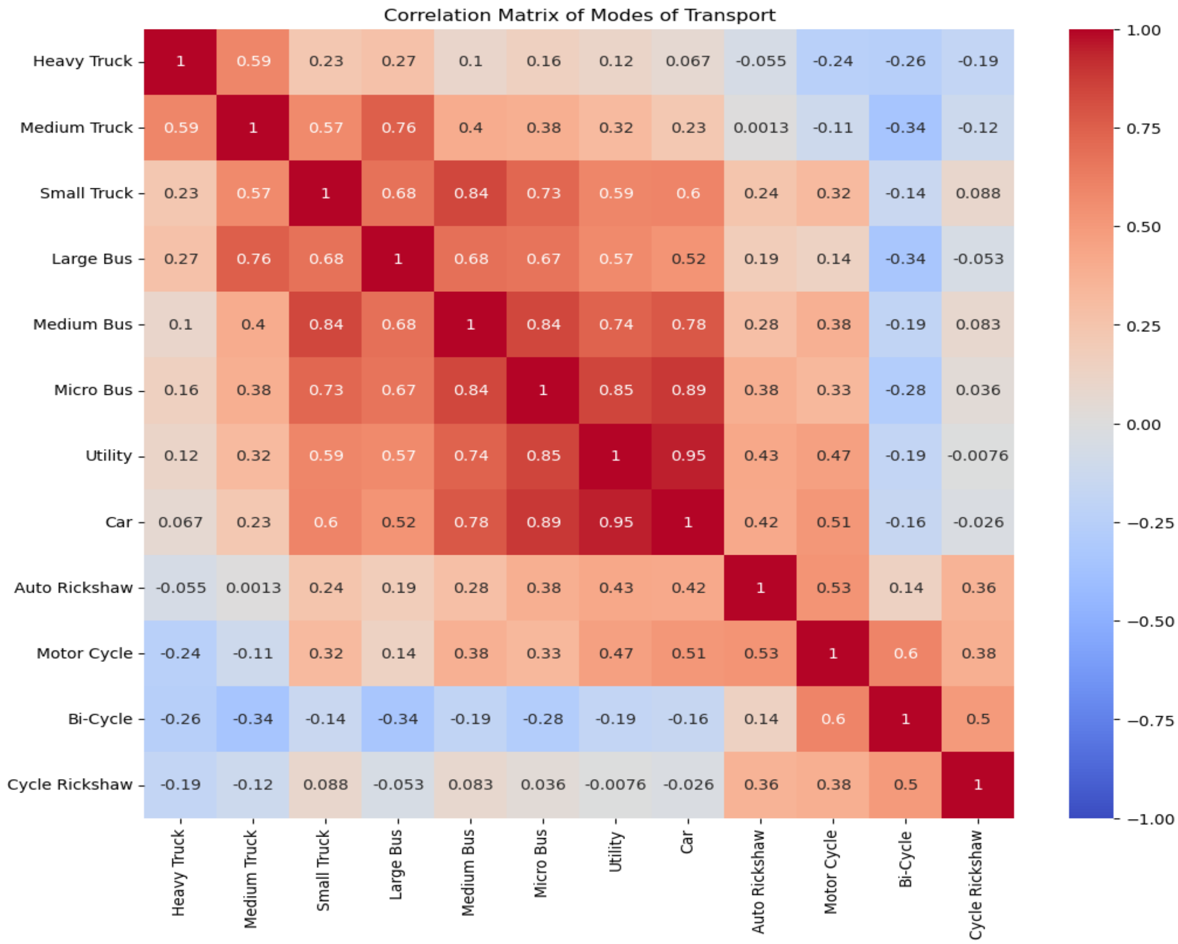

Figure 7. Heatmap of Correlations Between Traffic Volumes of Different Transport Modes

The correlation data (Figure 7) suggests that there are some strong relationships between different types of vehicles in Bangladesh. Specifically, the data shows strong positive correlations between certain types of trucks and buses, as well as between certain types of buses and cars. Conversely, there are also negative correlations between certain types of vehicles, such as motorcycles and bicycles, and larger vehicles like trucks and buses.

In the context of the transport network of Bangladesh, these findings have several implications. The strong positive correlations between certain types of trucks and buses, such as small trucks and medium buses, and between certain types of buses and cars, such as micro buses and cars, suggest that these vehicles may be used in similar ways or for similar purposes. This could be useful information for transportation planners and policymakers as they work to optimize the use of different types of vehicles in the country.

Additionally, the negative correlations between motorcycles and bicycles and larger vehicles like trucks and buses suggest that there may be safety concerns for these smaller vehicles on Bangladesh's roads. This makes sense, as we only investigate main roads (all N-roads), which are seen as Bangladesh's highway. It is remarkable, to actually observe bicycles on these roads and could indicate that the highways are not physically separated from other roads and are also used on small daily trips.

Overall, the correlation data provides valuable insights into the relationships between different types of vehicles in Bangladesh, and can be useful for transportation planners and policymakers as they work to improve and optimize the country's transport network.

4.2 Traffic Volume

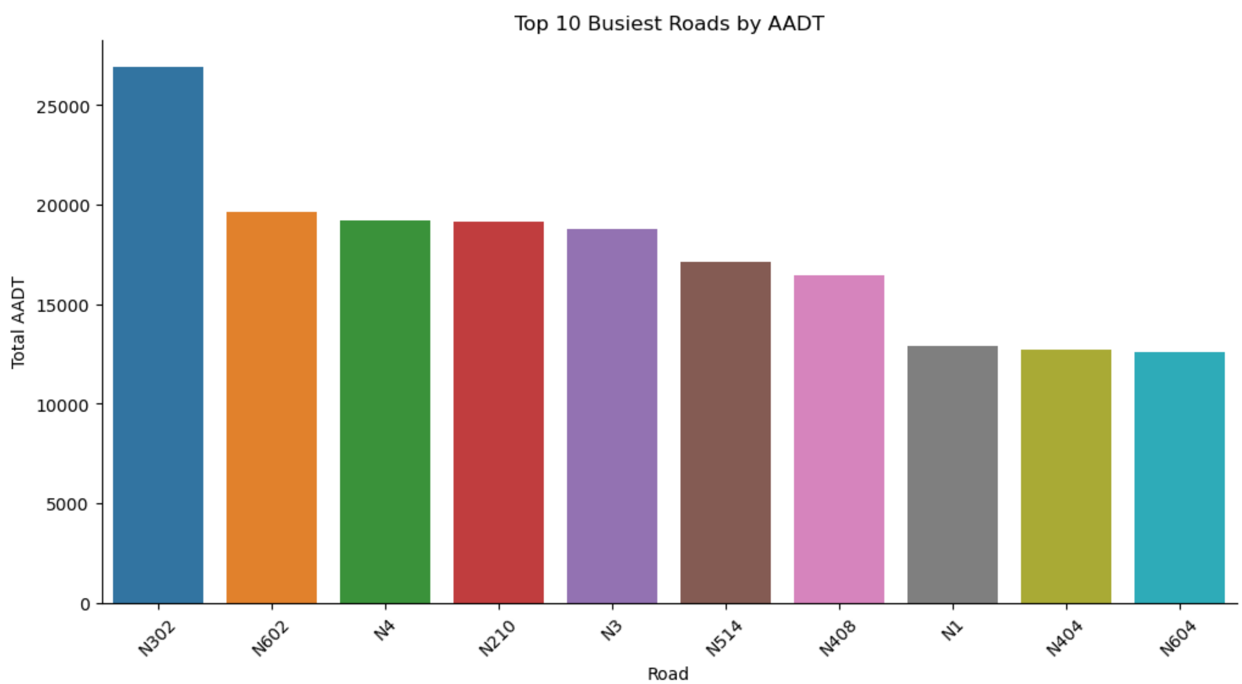

Figure 8. Bar Graph of Busiest Roads by Annual Average Daily Traffic

4.3 Graphical Exploratory Data Analysis

4.3.1 Volume by Road for Selected Modes of Transport

Seeing that Medium trucks are the most used mode of transport in Bangladesh, we extended our analysis by mapping the volume of road segments onto the map of Bangladesh to identify patterns and important areas.

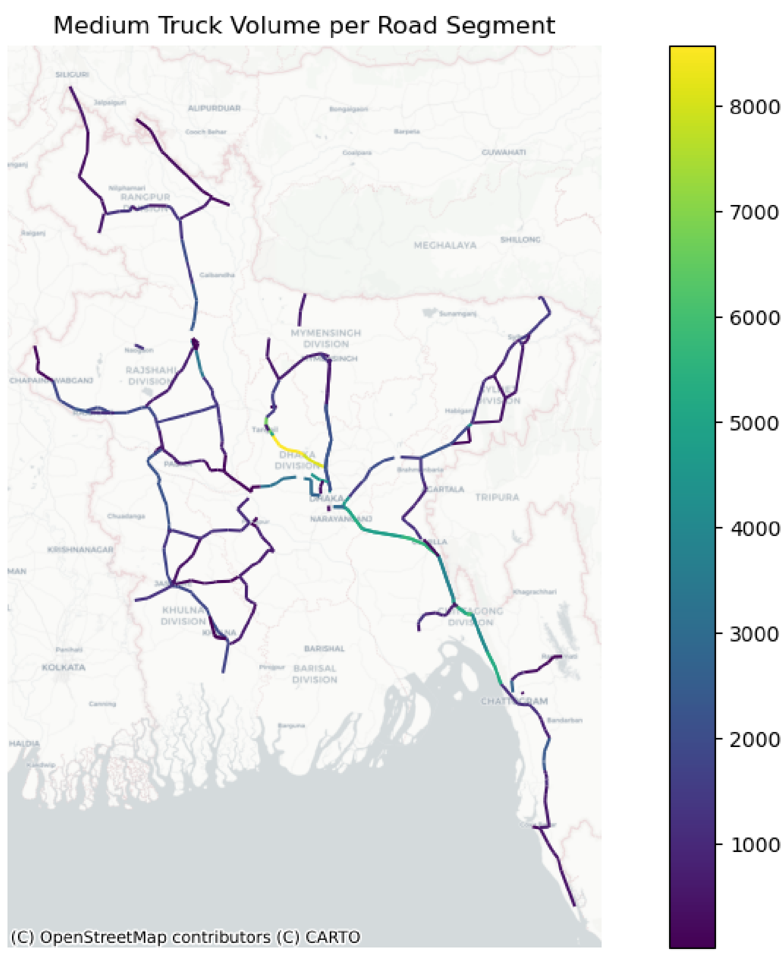

Figure 9. Map of Road Network coloured based on Traffic Volume of Medium Trucks

From Figure 9, we can conclude that medium trucks are especially relevant between Dhaka and Chittagong, seen by the green color. The N1 highway connects these two economically highly relevant cities. The relevance of this connection is represented by the high medium truck traffic which is a main mode of transporting economic goods.

In our previous EDA steps, we noticed that Auto Rickshaws are the most used mode of transportation. Hence, we also analyzed the auto rickshaw value geospatially to identify specific areas and connections that are highly relevant.

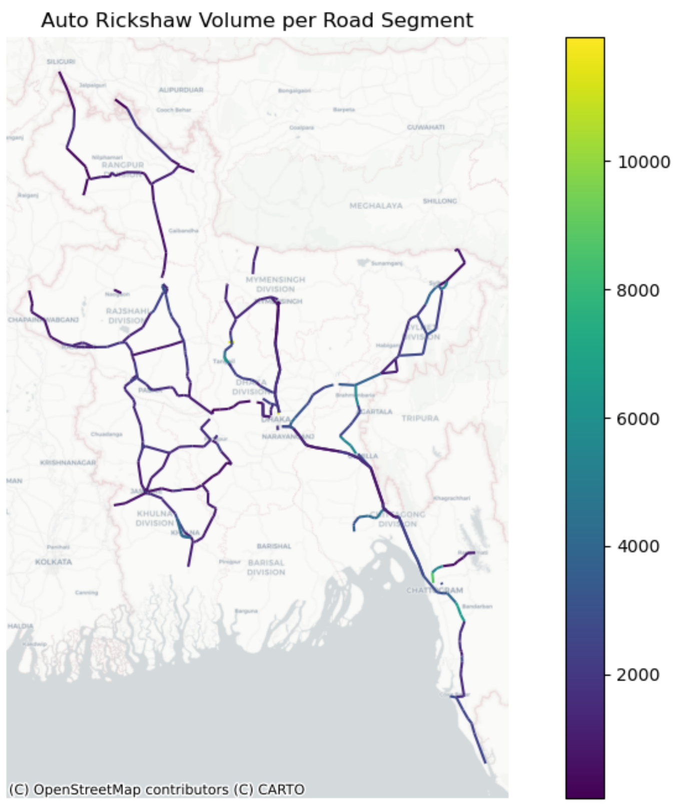

Figure 10. Map of Road Network Coloured Based on Traffic Volume of Auto Rickshaw

From Figure 10, we conclude that rickshaws are especially relevant in the proximity of bigger cities such as Dhaka or Chittagong. It seems that they are used for smaller distances and in areas that connect to the largest highways.

4.3.2 Flood Exposure Data

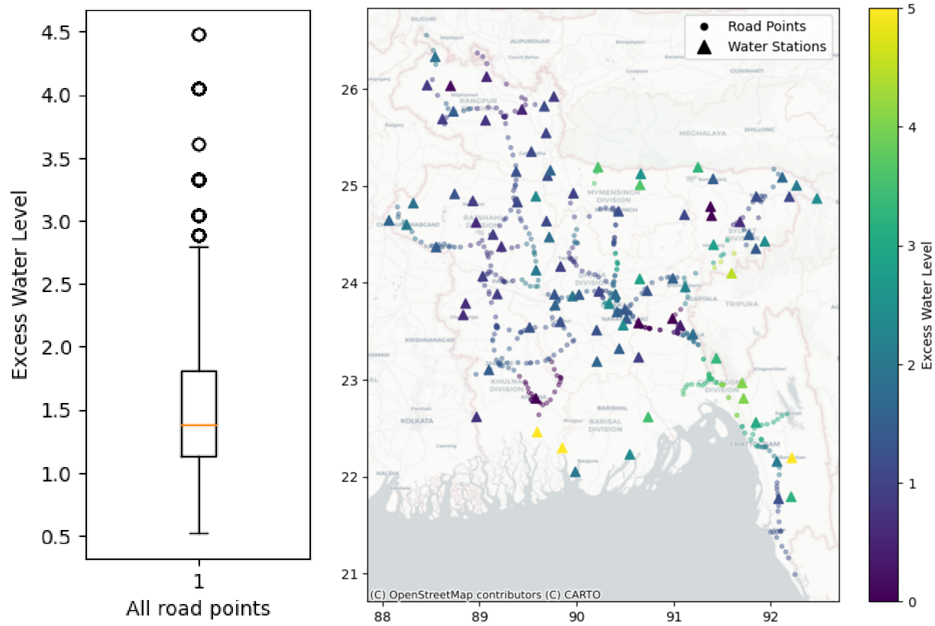

Figure 11. Graphs of Excess Water Level; Numerical Distribution (Left) Spatial Distribution (Right)

As illustrated in Figure 11, it seems that the nearest neighbor method was useful in allowing the spatial join between road points (dots) and flood exposure data at the water stations (triangles). With visual inspection, there is no unintended result of this join.

Roads with excess water levels (top 30) include N204, N207, N1, N402, N112 and N104. It seems that the high exposure road segments are generally quite spread out as opposed to clustered together.

5. Results

Bangladesh's transport network is threatened by flooding that can generate long-lasting interruptions due to damage in bridges. This poses a risk to the nation's social and economic wellbeing as road transport is the main transport method for goods and services. This risk can be reduced by infrastructure interventions in roads and bridges. To identify the top 10 most important interventions that can significantly reduce these risks, an assessment of road link vulnerability and criticality was conducted. This assessment was conducted using traffic, infrastructure and flooding data to calculate one Vulnerability Index and a Criticality Indicator that together denote the Importance of implementing intervention to road segments. The results provide valuable insights into the transportation network of Bangladesh and can help inform policy decisions regarding the improvement and development of the network.

5.1 Criticality

In this section, we analyze which infrastructure segments have the highest socio-economic **criticality** in regard to the transport of goods and present a top 10 of road segments.

Table 4. Top 10 Most Critical Road Segments with its Respective Criticality Indicators

Road Segment	Weighted Total Tons	Criticality Index
N106-1	3.59	1.00
N3-1R	2.57	0.71
N3-1L	2.42	0.67
N3-2R	2.41	0.67
N2-1	2.19	0.61
N2-2	1.98	0.55
N5-3L	1.96	0.54
N2-4	1.91	0.53
N2-3	1.91	0.53
N6-14	1.90	0.53

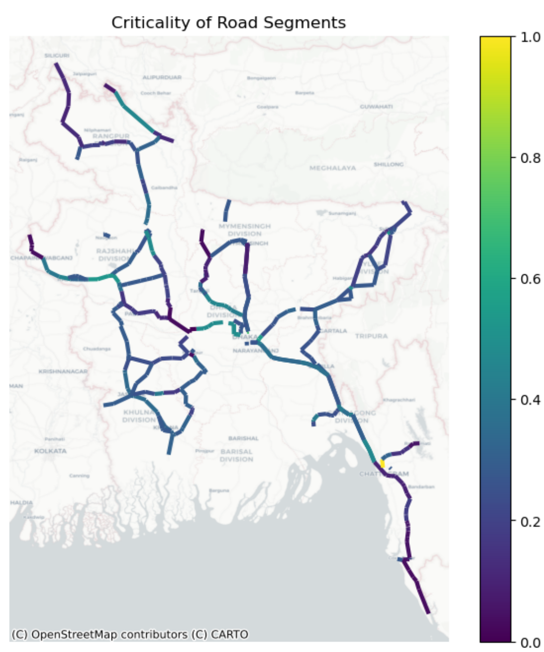

Figure 12: Map of Criticality Index for Road Segments

The data provided shows the top 10 most critical road segments in Bangladesh based on the criticality index that reflects the relative amount of transported goods in each segment.

The most critical road segment in Bangladesh is N106-1 with the highest criticality index. This road segment is likely to be a major transportation corridor that is essential for the movement of goods and people across the country. The second and third most critical road segments are N3-1R and N3-1L, respectively, with criticality indices of 0.72 and 0.67. These road segments are also likely to be major transportation corridors that are essential for the transportation network.

The remaining road segments in the top 10 list have criticality indices ranging from 0.61 to 0.53, indicating that they are also important for the transportation network in Bangladesh. These road segments are likely to connect major cities and regions within the country and facilitate the movement of goods and people.

5.2 Vulnerability

The vulnerability of transportation networks to natural disasters is a significant concern in many countries, including Bangladesh. In this section, we discuss **(Q2) -** which road segments contribute the most to the vulnerability of the multimodal transport network when exposed to natural hazards and present the results of our analysis of the vulnerability index of road segments in Bangladesh, based on their sensitivity, exposure, and adaptive capacity to natural hazards.

Our analysis has identified several road segments that are highly vulnerable to natural hazards and contribute significantly to the vulnerability of the multimodal transport network in Bangladesh. The vulnerability index of road segments is a composite index that takes into account their sensitivity, exposure, and adaptive capacity to natural hazards.

Table 5: Top 10 Most Vulnerable Road Segments With its Respective Vulnerability Indicators

Road Segment	Sensitivity	Exposure	Adaptive Capacity	Vulnerability Index
N1-68	1.00	0.60	0.02	0.54
N1-57	0.65	0.60	0.29	0.51
N1-11L	0.17	0.35	1.00	0.51
N2-13	0.62	0.71	0.03	0.45
N5-17	0.52	0.70	0.12	0.45
N106-3	0.48	0.82	0.02	0.44
N1-8L	0.46	0.62	0.23	0.44
N106-2	0.45	0.82	0.03	0.43
N2-11	0.13	0.63	0.53	0.43
N302-3	0.54	0.66	0.09	0.43

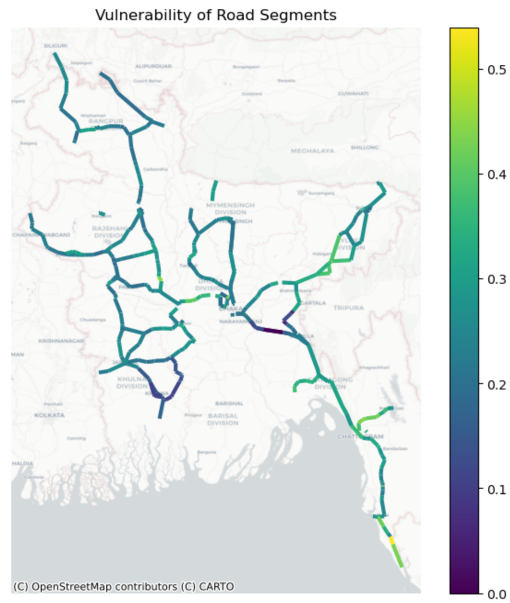

Figure 13: Map of Vulnerability Index

The most vulnerable road segment identified in our analysis is N1-68, with a vulnerability index of 0.539749. This road segment has a sensitivity index of 1.000, indicating that it is highly sensitive to natural hazards, and an exposure index of 0.595268, indicating that it is frequently exposed to natural hazards. However, its adaptive capacity index is relatively low, indicating that it may be challenging to adapt to the effects of natural hazards on this road segment.

Several other road segments in our analysis were also identified as highly vulnerable to natural hazards and contribute significantly to the vulnerability of the multimodal transport network in Bangladesh. These road segments include N1-57, N1-11L, N2-13, N5-17, and N106-3. These road segments have vulnerability indices ranging from 0.432 to 0.510, indicating that they are susceptible to the effects of natural hazards and require attention for improvements and adaptations.

5.3 Importance

Based on both criticality and vulnerability, we analyzed which are the most important infrastructure segments in the multimodal transport network of Bangladesh and provided a top 10 list.

Table 6: Top 10 Most Important Road Segments with its Respective Criticality and Vulnerability

Road Segment	Criticality Index	Vulnerability Index	Importance Index
N106-1	1.00	0.38	0.69
N3-1R	0.71	0.22	0.47
N3-1L	0.67	0.25	0.46
N2-4	0.54	0.39	0.46
N3-2R	0.67	0.22	0.45
N2-1	0.61	0.28	0.44
N5-9	0.48	0.40	0.44
N5-8	0.48	0.40	0.44
N1-11L	0.37	0.51	0.44
N5-2L	0.48	0.40	0.44

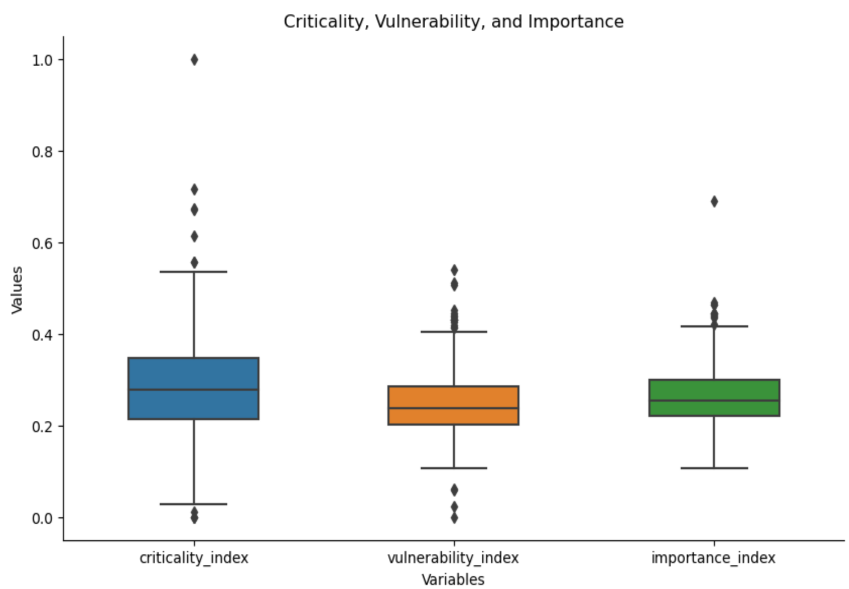

Figure 14. Box Plot Illustrating the Range of Criticality, Vulnerability and Importance

The data provided shows the top 10 most important road segments in Bangladesh based on the criticality index, vulnerability index, and importance index. The criticality index measures the level of criticality of a road segment based on the weighted total tons that pass through it. The vulnerability index measures the vulnerability of a road segment to natural disasters, such as flooding. The importance index is a composite index that takes into account both the criticality and vulnerability indices to identify the most important road segments in the transportation network.

The most important road segment in Bangladesh is N106-1 with the highest criticality value and a vulnerability index of 0.38, resulting in an importance index of 0.69. This road segment is likely to be a major transportation corridor that is essential for the movement of goods and people across the country. The second and third most important road segments are N3-1R and N3-1L, respectively, with important indices of 0.47 and 0.46. These road segments are also likely to be major transportation corridors that are essential for the transportation network.

The remaining road segments in the top 10 list have important indices ranging from 0.44 to 0.44, indicating that they are also important for the transportation network in Bangladesh. These road segments are likely to connect major cities and regions within the country and facilitate the movement of goods and people.

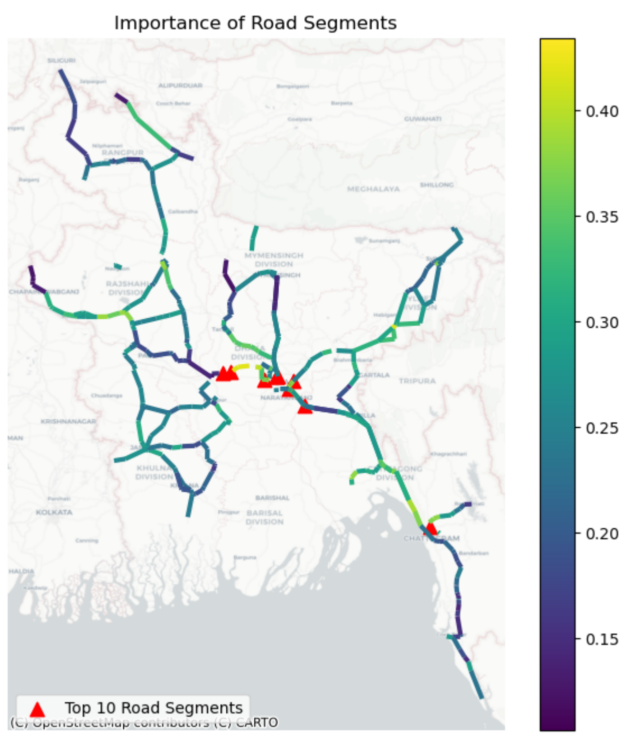

Figure 15: Map of Road Network with the Top 10 most Important Road Segments represented by Red Triangles

Table 7: Top 10 most Important Bridges with its Respective Vulnerability Indicators

Bridge Name	Length [m]	Condition
Natunpara Bridge	19	C
NOTUN PARA	18	B
DAWANNAGOR CULVERT	10	C
BORODIGHIR PAR	9	C
CHOWDIRIR HAT	6	C
PASSIM SURAGOL	9	B
BORDIGHIR PAR	5	C
11 MILE BOX CULVERT	4	C
Modarhat Bridge	13	A
LALIYAR HAT	3	C

Given Table 7, we saw that the road segment N106-1 is the most important in Bangladesh's transport network. Hence, we analyzed the top 10 bridges in that segment by weighting the length with the condition given the factors used in the sensitivity formula in section 2.2 (Table 3). We see that longer bridges with a worse condition are especially relevant within the most important road segment. The same calculation could be done for every important road segment to assess which bridges should be maintained first.

6. Discussion and Limitations

Our analysis of the transportation network in Bangladesh has revealed several potential areas for intervention. One of the most significant findings is that medium trucks and auto-rickshaws are the most commonly used mode of transport for goods and people, respectively. This suggests that the transportation network in Bangladesh primarily caters to the needs of small and medium-sized businesses, as well as individuals who rely on auto-rickshaws for daily commuting.

Another important finding is the vulnerability of the transportation network to flooding, with critical road segments identified as being at risk of disruption. This highlights the need for investment in infrastructure and adaptation measures to help mitigate the impact of natural disasters on the transportation network.

Additionally, our analysis of the criticality, vulnerability, and importance of road segments has identified key routes that are critical for the transportation network. The most critical road segment is N106-1, with a criticality index of 1.000 and an importance index of 0.69. This road segment is likely a major transportation corridor essential for the movement of goods and people across the country. Our analysis also identified several other road segments that are critical and require attention for improvements and adaptations.

Overall, our analysis highlights the need for investment in infrastructure and adaptation measures to improve the resilience and efficiency of the transportation network. These findings can inform policy decisions regarding the development and improvement of the transportation network in Bangladesh and serve as a valuable resource for stakeholders involved in the transportation sector.

A limitation of our assessment is in the form of our numerical approximations. Throughout this report, several mathematical methods were utilized in order to compare criticality and vulnerability indicators effectively. Some examples are the weighted sums, calibrated factors, and cohesive index measurement. It can be seen as a source of uncertainty and inaccuracy, but we argue that this is a proof of concept necessary to converge on a ‘top 10’ assessment. With better calibrations in the future, our assessments can be further improved.

For future work, we recommend expanding the scope of critical analysis to incorporate a more human-centric perspective, prioritizing the movement of people rather than solely focusing on the transportation of economic goods. This approach would offer a broader understanding of the transportation network's criticality and its impact on society as a whole.

Additionally, this report has analyzed Bangladesh's transportation system at a national level, aggregating the data across the entire country. Future studies could build upon our existing framework and perform more granular analyses at smaller aggregation levels, such as Zilas and Upazilas. By doing so, these projects would be able to provide more functional and targeted policy recommendations, addressing the specific needs and challenges faced by local administrations.

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Appendix A

Table A1: Representative Models of RHD Vehicles (Ministry of Road and Bridges, 2017)

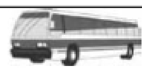
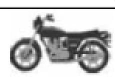
No	Picture	RHD Category	Description and Representative Models
a) Motorised Vehicle			
1.		Heavy Truck	Trucks with three or more axle which includes multi-axle tandem trucks, container carriers and articulated trucks. **Model: Tata LPT 2516**
2.		Medium Truck	Trucks with two axles and carries over three tonnes payload. **Model: Tata LPT 1615**
3.		Small Truck	Smaller Trucks which carries up to three tonnes payload. **Model:Tata LPT 407**
4.		AC Bus	Large Buses with more than 40 seats on 36 feet or longer chassis having direct or fewer stop service with Air Conditioning System. **Model: Hino AK1J/ LPO 1316**
5.		Chair Class Bus	Large Buses with more than 40 seats on 36 feet or longer chassis having fewer stop services without Air Conditioning System. **Model: Hino AK1J/ LPO 1316**
6.		Ordinary Large Bus	Large Buses with more than 40 seats on 36 feet or longer chassis having more frequent stop services without Air Conditioning System. **Model: Hino AK1J/ LPO 1316**
7.		Mini Bus	Smaller Buses with 16 to 39 seats and less than 36 feet chassis **Model: Tata LP909**
8.		Micro Bus	Upto16 seats. **Model: Toyota Hiace**
9.		Utility	Pick-up, jeeps and four wheeled drive vehicles. **Model: Toyota Land Cruiser Prado/ Toyota Hilux**
10.		Car	All types of car used either for personal or taxi services. **Model: Toyota X-Corolla**
11.		Motor Cycle	All two wheeled motorised vehicles **Model: Bajaj Platina 100cc**
12.		Auto Rickshaw	Motorised three wheeled vehicles. **Model: Bajaj Baby Taxi**
13.		Tempo/ Human Hauler	Large passenger & cargo carrying 3/4 wheelers. **Model: Tata Shaathi**
b) Non-Motorised			
14.		Cycle Rickshaw	Three wheeled non- motorised vehicles
15.		Bicycle	All pedal cycles.

Table A2:Cargo Value for National/Regional Highways (Ministry of Road Transport and Bridges, 2017)

Parameters	Heavy Truck	Medium Truck	Small Truck
AC (Ton)	28	14	5
UV (TK)	75,322	71,570	60,363
I (12% per year equivalent to 0.000014/hr)	0.000014	0.000014	0.000014
E	20%	20%	20%
Value of Cargo Time (TK per veh-hr)	23.4	10.9	3.4
Economic VOC (TK/Hr)	1405.5	870.6	634.7
Cargo Time /Economic VOC	2%	1%	1%

Table A3:Vehicle characteristics: weights and dimensions (Ministry of Road Transport and Bridges, 2017)

Category	Model	Axle No.	Unloaded Weight Kg	Gross Vehicle Weight Kg	Length mm	Width mm	Height mm
Heavy Truck	Tata LPT 2516	3	6,300	25,000	9,010	2,465	2,943
Medium Truck	Tata LPT 1615	2	5,430	16,200	8,395	2,440	3,600
Small Truck	Tata LPT 407	2	2,530	6,250	5,000	1,650	2,200
Chair Class Bus	Hino AK1J	2	4,405	14,200	11,080	2,410	1,975
Mini Bus	Tata LP909	2	3,300	9,000	5,970	2,159	1,900
Micro Bus	Toyota Hiace	2	1,940	3,000	4,840	1,880	2,105
Utility	Toyota Land Cruiser Prado	2	2,375	2,990	4,930	1,885	1,845
Car	Toyota X-Corolla	2	1,260	1,635	4,620	1,776	1,475
Tempo	Tata Saathi	2	710	1550	3,800	1,500	1,861
Auto Rickshaw	Bajaj Baby Taxi	2	348	678	2,635	1,300	1,710
Motor Cycle	Bajaj Platina 100	2	108	180	2,000	840	1,060

Appendix B

To determine the progression factor that would define the slope of the exponential relation between our input values and the sensitivity and adaptive capacity indicators, an iterative process was conducted. The basic narrative behind this experiment is that conducting works in one 1,800 m bridge should require more support than on two bridges with half the length. In other words, the adaptive capacity index should prioritize fixing one road segment that has long bridges over one that has smaller bridges even if both have the same total length of bridges.

In the Figure below, we compare 4 combinations of bridges that have the same total length and we compute the adaptive capacity indicator with different progression factors. A progression factor of 1 means that all combinations have the same values of adaptive capacity. A progression factor of 2 generates a very aggressive slope where the adaptive capacity is halved for each subsequent combination. To reduce uncertainty, a 1.2 progression factor was selected that generates a non aggressive slope but maintains an exponential relation.