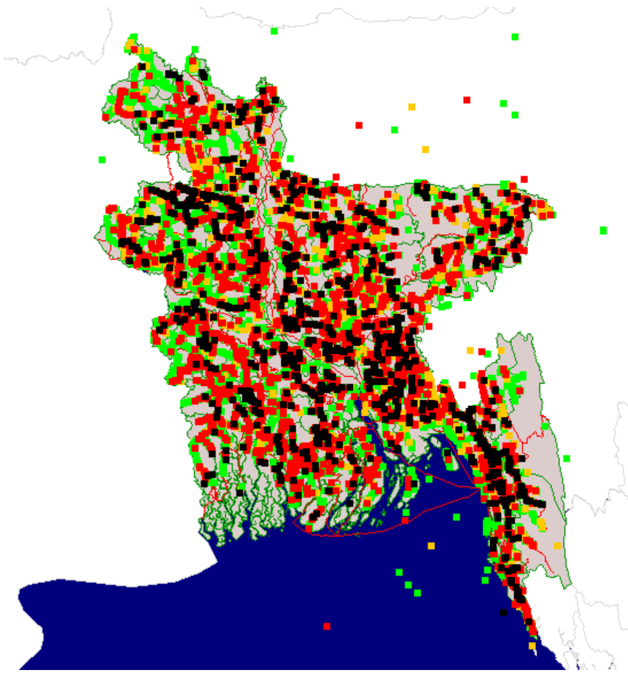
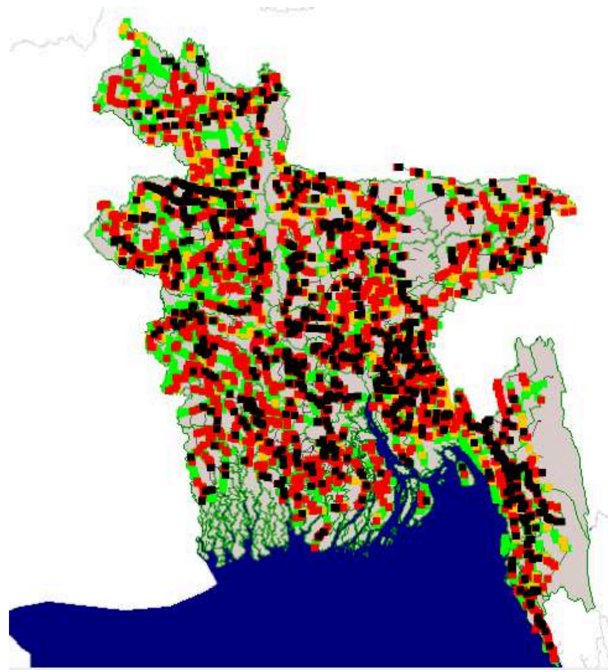
Report Assignment 1

EPA1352: Advanced Simulation





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Words: 4651

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1. Context

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 that make the livelihood and economy heavily rely on its transport infrastructure with a focus on bridges. Some bridges are up to 6 km long and act as a bottleneck in the transport network.

To analyze the data quality and potential types of issues, it is important to be aware of the research's context and hence, its research questions:

1. Which are the most **critical** infrastructure elements in the multimodal transport network of Bangladesh?
2. Which elements contribute most to the **vulnerability** of the multimodal transport network when exposed to natural hazards and what are the socio-economic consequences when exposed to different hazards?
3. What are the most robust interventions to enhance the overall **resilience** of the transport network?

The research questions show that criticality and vulnerability factors are essential in this research. Firstly, the factors help evaluate and understand Bangladesh's transport infrastructure's current situation and state. In addition, the factors are of great use when examining the socio-economic impact of natural hazards. Lastly, both criticality and vulnerability play an important role when assessing potential policies' impact on the transport network's resilience. The resilience of a network will increase when there are fewer critical and vulnerable elements. It is, therefore, important to determine the criticality and vulnerability in a reliable and thorough way.

Two datasets are available for use in this analysis. The following two paragraphs aim to describe the *What, When, Where, How, Who, Which,* and *Why* of both datasets. These data quality aspects enable other researchers to replicate our research - a critical element of scientific investigation and analysis (Marsden & Pingry, 2018).

The first dataset is the Road Maintenance and Management System (RMMS) database of the Roads and Highway Department (RHD) of the Bangladeshi Ministry of Road Transport and Bridges. The RHD is responsible for managing and maintaining the major road network in Bangladesh, including National Highways, Regional Highways, and Zilla Roads (HDM Circle, 2020). The main purpose of the RMMS database is to develop plans for maintenance (Khan & Odoki, 2010). The dataset was developed in 2004 when RHD undertook a major survey of its network covering around 15,000 km of roads. This comprehensive survey included a full inventory, current condition, pavement structure, and traffic flows. In subsequent years, the dataset was kept up to date by conducting further surveys.

The second dataset is the RHD's Bridge Maintenance and Management System (BMMS) database. This BMMS dataset has direct links to the RMMS dataset. The goal and way of setting up the RMMS dataset are similar. Just like RMMS, the BMMS dataset is used to manage bridges and plan maintenance. The data was also collected through extensive surveys, which sometimes raised problems due to low response (Adhikary, 2019). The dataset contains information about bridges with location, structure, substructure, condition, and maintenance.

Data quality is possibly the most important aspect of properly determining the criticality and vulnerability of the infrastructure elements. Cleaning the data by fixing structural errors, filtering unwanted outliers, and handling missing data is very important. This ensures that our dataset's data points are accurate and complete. If not, data points not correctly connected to the network could falsely assume a higher criticality or vulnerability of network points. Moreover, important transport bottlenecks, such as bridges, could be missed. Different data-cleaning steps are performed to prevent this from happening.

2. Strategy

The data cleaning and quality assurance process is essential in ensuring that the data used for analysis is accurate and reliable. This section aims to outline the strategy employed in the following report to provide a conceptual framework to identify, prioritize, and solve potential data quality issues.

To achieve this, we will adopt the semiotic information quality framework developed by Price and Shanks (2005). This framework provides a structured approach to categorizing data quality issues. By utilizing this framework, we can systematically identify and address potential data quality issues, ensuring

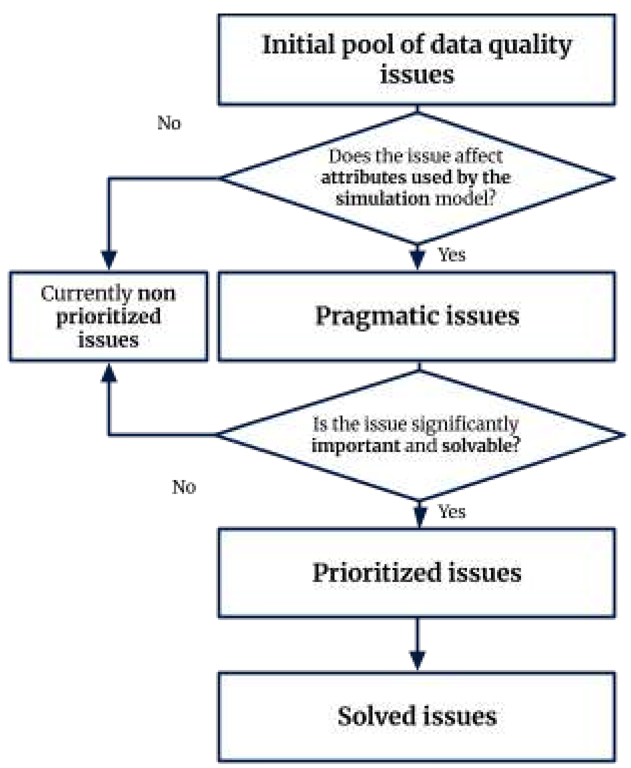


Figure 1. Data quality issues handling strategy outline

that the data used for analysis is of the highest quality possible given the time constraint.

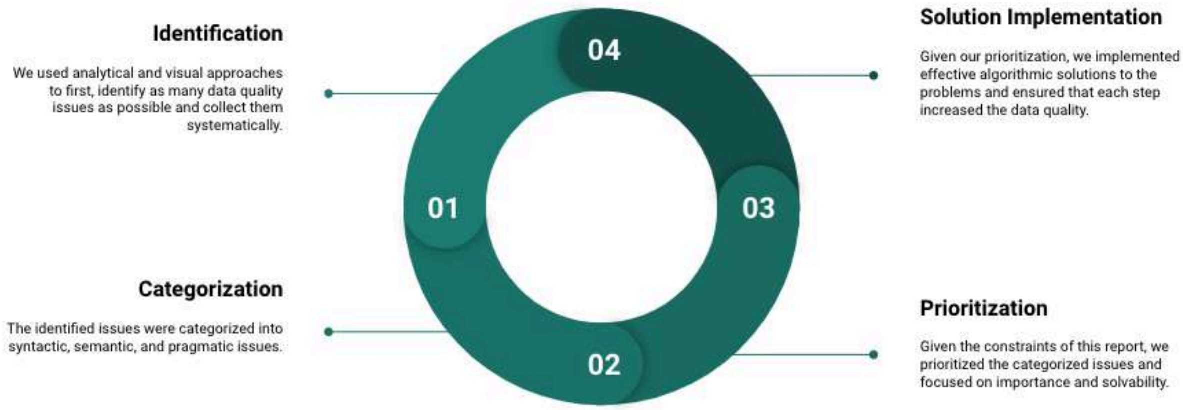


Figure 2. *Stepwise Strategy of Data Cleaning*

Once the data quality issues have been identified and categorized, pragmatic issues will be prioritized based on their importance and solvability. This will enable us to determine which issues must be addressed first to ensure the data is reliable and accurate. By prioritizing the most important and solvable issues, we can ensure that our efforts are focused on the areas that will have the greatest impact on the quality of the data.

Finally, once the prioritization process is complete, algorithmic solutions will be presented. These solutions will be based on the final prioritization and will address the most important and solvable data quality issues.

Overall, this strategy aims to provide a comprehensive approach to data cleaning and quality assurance, ensuring that the data used for analysis is of the highest quality possible. By following this strategy, we hope to provide reliable and accurate insights that can be used to inform decision-making processes.

In the end, the limitations of the report are discussed to further reflect on its strategy and applied methods. Furthermore, we discuss potential extensions of our approach for future projects.

3. Conceptual Analysis of Data Quality Issues

To evaluate the quality of data, Price and Shanks (2005) introduced three dimensions; the syntactic, semantic, and pragmatic dimensions. We adapt this framework in the sense that, first, all data quality issues are categorized according to their intrinsic syntactic and semantic nature. Afterward, those issues will be structured according to the context of this and the following assignments (business-world alignment). Thus, the amount of data quality issues is scoped down to pragmatic data quality issues only, and hence syntactic and semantic data quality issues that have no effect on the simulation are not considered - see Figure 3. This way, we account for both; the context and time constraints.

Figure 3. *Venn Diagram of Syntactic, Semantic and Pragmatic Quality*

3.1 Syntactic Data Quality Issues

The syntactic dimension focuses on the structure and format of data, including its accuracy (Scannapieco et al. 2005; Batinit et al., 2009) and consistency (Pipino et al., 2002; Loshin, 2011). In the context of our data, this would comprise general integrity rules relating to issues such as the definition, documentation, and representation of data (i.e. the data schema of how road information is structured should follow a set of rules; operationalized by the Ministry of Transport from Bangladesh).

3.1a Syntactic Accuracy

Taking the criteria of syntactic accuracy - conformity of data values with respect to the corresponding definition of the data value, we identified that **missing data values are represented as NULL values** although the **domain uses numerical data values**.

StructureName	StructureI	ReferenceI	Location	LocationC	LatitudeD	LatitudeN	LatitudeS	Longitude	Longitude	Longitude	NumberO	Construct	StructureTypeDesc
Nakatibhanga Bridge.	LRP005a	LRP005	20	5.02	23	39	55.2	90	37	37	1	2010	RCC Girder Bridge
Khongshardi Bridge	LRP006a	LRP006	668	6.119	23	40	23.9	90	37	50.2	3	2008	RCC Girder Bridge
Bhairobertek Bridge	LRP002a	LRPS	2650	2.65	23	45	35.2	90	35	14.7	1	1994	RCC Girder Bridge
Ambag Bridge	LRP004c	LRPS	4780	4.78	23	44	37.9	90	34	45.2	3	NULL	RCC Girder Bridge
Perabo Bridge	LRP005a	LRP005	710	5.71	23	44	41.2	90	34	16.4	NULL	2000	RCC Girder Bridge
Oirabo Bridge	LRP006a	LRP005	1600	6.6	23	44	48	90	33	42	3	1972	RCC Girder Bridge
Gasua Santoshpur Bridge	LRP018b	LRP018	850	17.23	22	32	11.9	91	28	9.6	1	1994	RCC Girder Bridge

Figure 4. *Error of Data Conformity*

3.1b Syntactic Consistency

Another syntactic data quality criterion which describes the syntactic quality is consistency. Since the data was collected by different divisions within the Ministry of Transport, **different naming conventions** were used (named according to start and end city; other descriptions; or landmarks).

Cox's Bazar-1	Z1130	Dulahazra-Garzania-Kasharia-Baisari Road	Sogir Kata Bridge
Cox's Bazar-1	Z1130	Dulahazra-Garzania-Kasharia-Baisari Road	Bendar Para Bridge
Cox's Bazar-1	Z1131	Khutakhali-Maheshkhali Road	Medha Bridge
Cox's Bazar-1	Z1132	Khuruskul Bridge-Chowkoldandi-Eidgah Road	Khursukul Bridge
Cox's Bazar - 2	Z1133	Whykhong-Shaplapur Road	Joarkhali Bridge
Cox's Bazar - 2	Z1133	Whykhong-Shaplapur Road	Koichong Bridge
Cox's Bazar - 2	Z1133	Whykhong-Shaplapur Road	Shaplapur Bridge
Cox's Bazar - 2	Z1133	Whykhong-Shaplapur Road	Lamar Bazar Bridge
Feni-2	Z1134	Feni (Masterpara)-Alokdia-Valukdia-Laskerhat-Ch	Shopno Bridge
Feni-2	Z1134	Feni (Masterpara)-Alokdia-Valukdia-Laskerhat-Ch	Kachua pul Bridge
Feni-2	Z1134	Feni (Masterpara)-Alokdia-Valukdia-Laskerhat-Ch	Nita Kagi Bridge
Brahmanbaria	Z1201	Kashba-Kuti Road	Kuthi bazar Steel Bridge
Brahmanbaria	Z1201	Kashba-Kuti Road	Hatgeccha Bridge

Figure 5. *Error of Road Naming Convention*

3.2 Semantic Data Quality Issues

The semantic dimension looks at the meaning of data, including its semantic **accuracy** (Fox et al. 1994; Redman, 1996; Price and Shanks, 2005), semantic **completeness** (Redman, 1996; Bovee et al. 2003; Price and Shanks, 2005) and mapping **consistency** (Price and Shanks, 2005). Thereby, it focuses on issues that relate to the transformation of real-world states to information system representations. Therefore, identifiable IS data units (i.e. Road file for N1) represent external phenomena (the real road).

3.2a Semantic Accuracy

As most of the provided data by the Ministry of Transport was collected by hand, it is prone to human errors. As a result, identifiable data units do not represent external phenomena. To differentiate semantic accuracy from semantic completeness issues we define any data value that exists (not NULL) but is inaccurate as semantic accuracy issues. Several errors have been identified.

Latitude and Longitude Errors

Road visualizations are subject to spikes due to inaccurate coordinates. The spikes are visible in Figure 6. The wrong Latitude and Longitude data, most likely caused by typos, is visible in Figure 7.

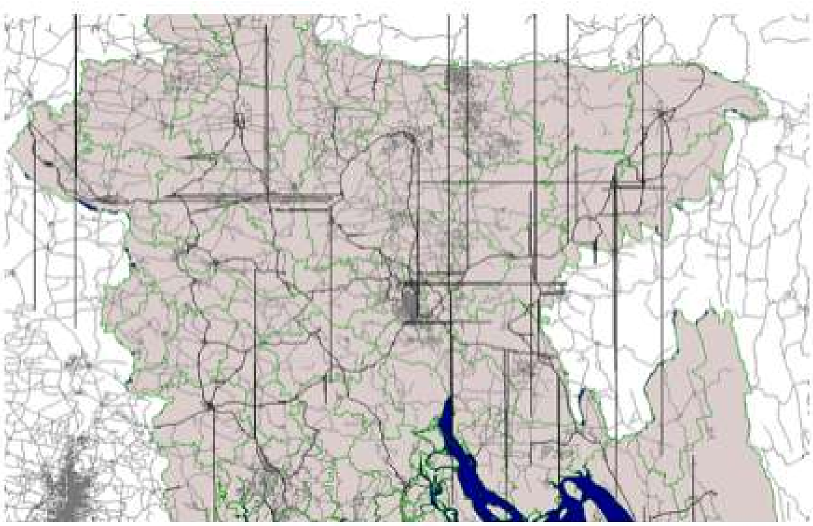
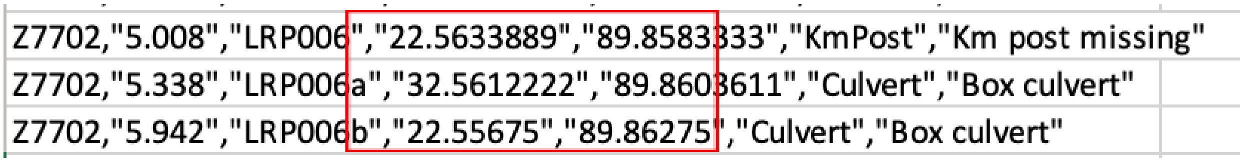


Figure 6. *Road spikes on map*



Z7702,"5.008","LRP006","22.5633889","89.8583333","KmPost","Km post missing"	
Z7702,"5.338","LRP006a","32.5612222","89.8603611","Culvert","Box culvert"	
Z7702,"5.942","LRP006b","22.55675","89.86275","Culvert","Box culvert"	

Figure 7. Error of Road Location

Inaccurate Location of Bridges

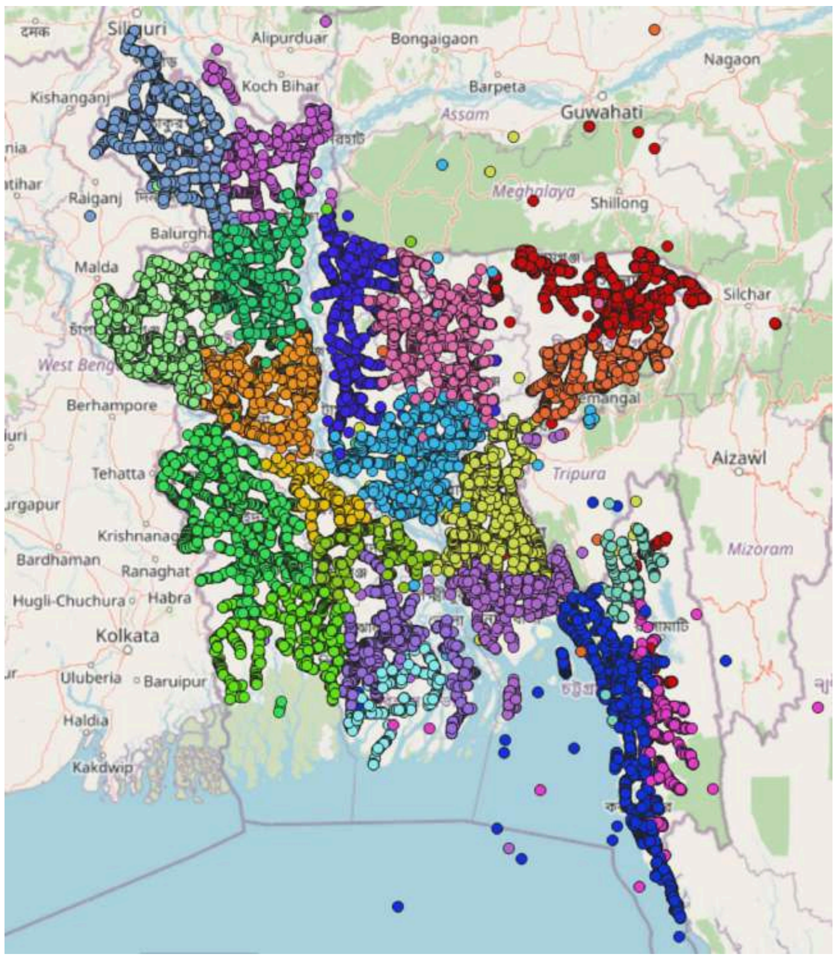


Figure 8. Overview of Bridge Clusters to identify Location Errors

Bridges outside their clusters (i.e. bridges outside of Bangladesh) clearly show inaccurate coordinates. Clusters were defined according to Bangladesh's main divisions.

Inaccurate Length of Bridges

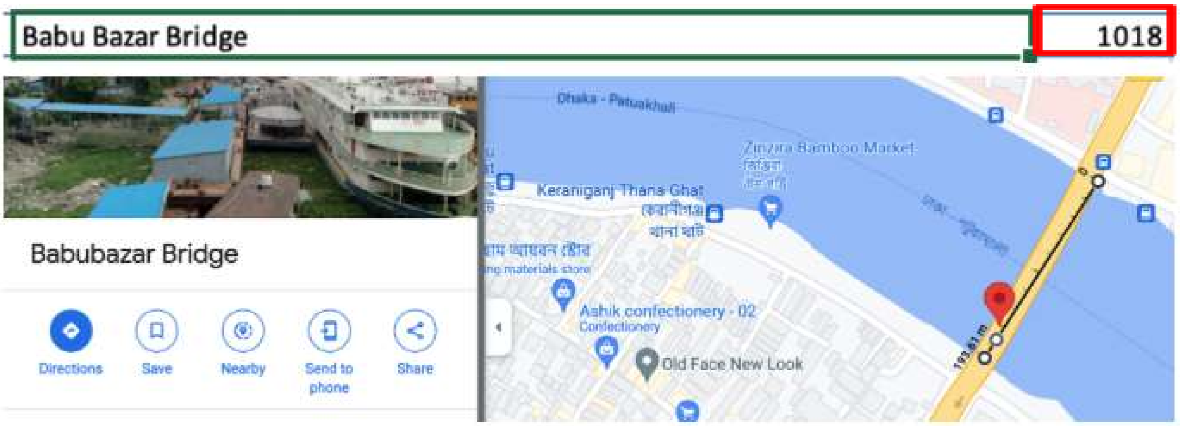


Figure 9. *Error of Length Accuracy for Babu Bazar Bridge*

The example of the Babu Bazar Bridge illustrates the issues since an inaccurate bridge length of 1018m is recorded (Google Maps represents it with a span of 193m).

Multiple Bridge & Road Entries

Figure 10. *Error of Multiple Bridge Entries*

LRP019a and LRP058c are both the same SHIBPUR RCC GIDER BRIDGE. Both entries have different lengths and widths, whereas in reality there is only one bridge as can be seen in the right picture.

R745	96.445	LRP098	23.5669716	88.9765549	KmPost	Km post missing
R745	96.801	LRP098a	23.5659444	88.9798327	Others	Jhenaidah RHD start
R745	96.801	LRP098a	23.5659444	88.9798327	Others	Jhenaidah RHD start
R745	97.705	LRP099	23.5645278	88.9876941	KmPost	Jhenaidah 19 km,Magura 42 km
R745	98.325	LRP099a	23.5637222	88.9937774	Culvert	Box culvert

Figure 11. *Error of Multiple Road Entries*

Moreover, there is a duplicate road entry. The LRP098a from road R745 is twice in the dataset, as can be seen in Figure 11.

Inaccurate Road Intersections

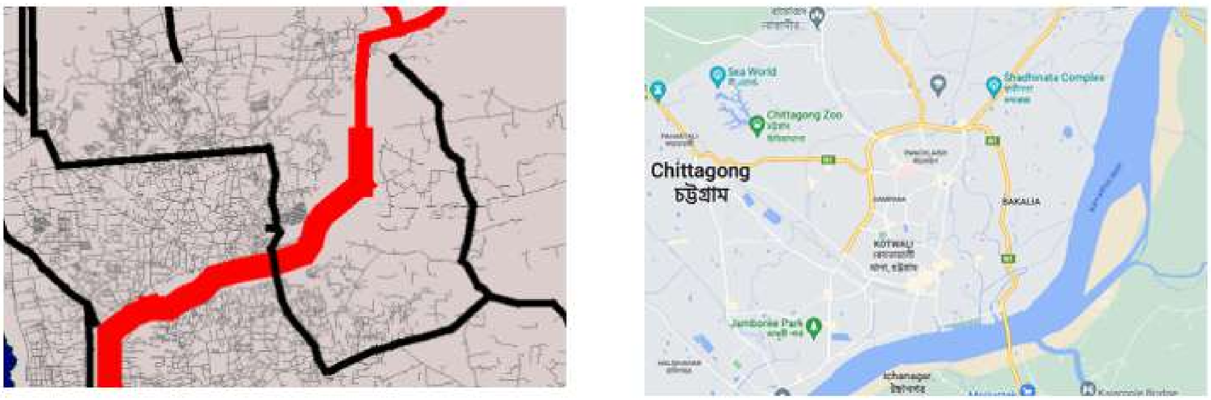


Figure 12. *Error of Road Intersections for N1, N107, and N106*

The LRPs are not accurate enough to represent all road intersections. For instance, in Chittagong, the national roads N1, N106, and N107 intersect (see Google Maps), which is not accurately represented in the data.

3.2b Semantic Completeness

The criteria of semantic completeness helps to assess which existing values are represented within our datasets and which are not. Thus, we define data quality issues that arise due to the mere non-representation of data - missing data, as semantic completeness data quality issues. The following missing data values are found.

Construction years

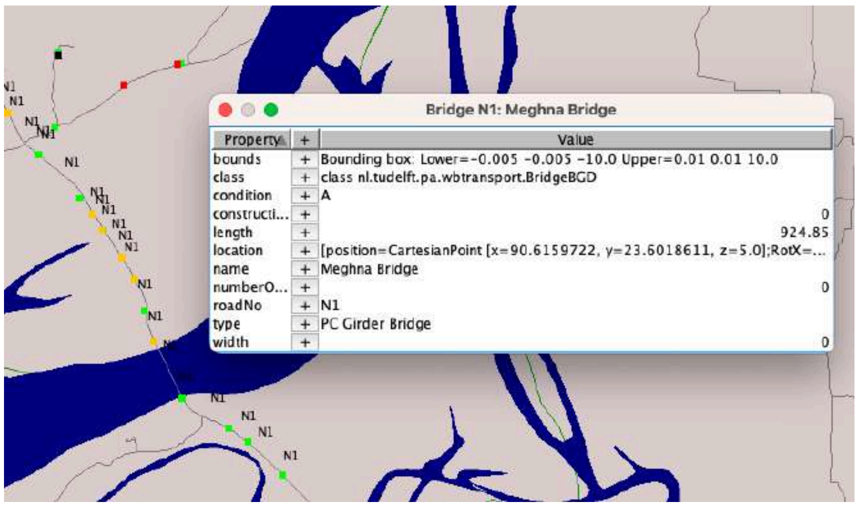


Figure 13. Error when Construction Year is Missing

The Meghna Bridge was completed in 1991, but this is not mentioned in the data. Only the number zero is shown in the construction year in Figure 13.

Bridge Names

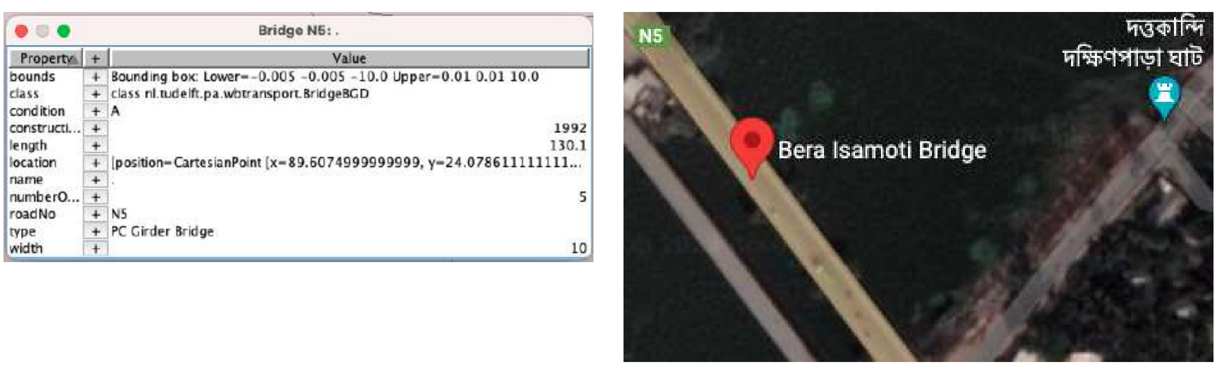


Figure 14. Error Example of Road Naming

Some bridge entries are missing the name. For example, the Bera Isamoti is missing its name in the dataset, right now it is represented by a dot. The rest of the information is correct.

Missing Bridges

Another example of missing data is bridges that are recently built, so they are not included in the data. An example of this is the famous and important Padma Bridge. In Figure 15 the bridge is missing on the left but was completed in June 2022.

Figure 15. *Error Example of Missing Bridges*

Length of Bridges

The length of the Kanchpur Bridge near Dhaka is missing. However, the width of 18.4 meters can be found online. The data is thus incomplete.

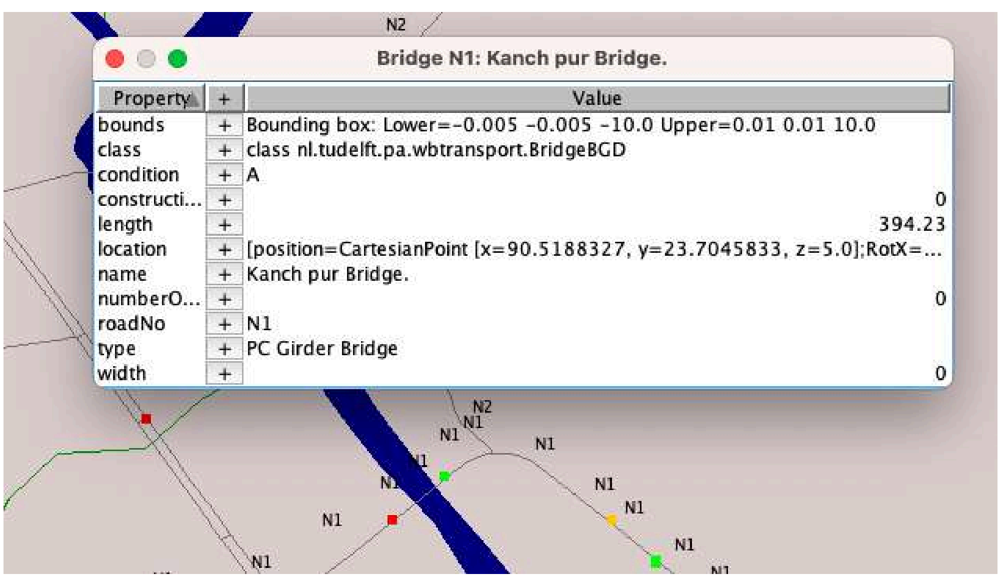


Figure 16. *Error Example of Missing Bridge Length*

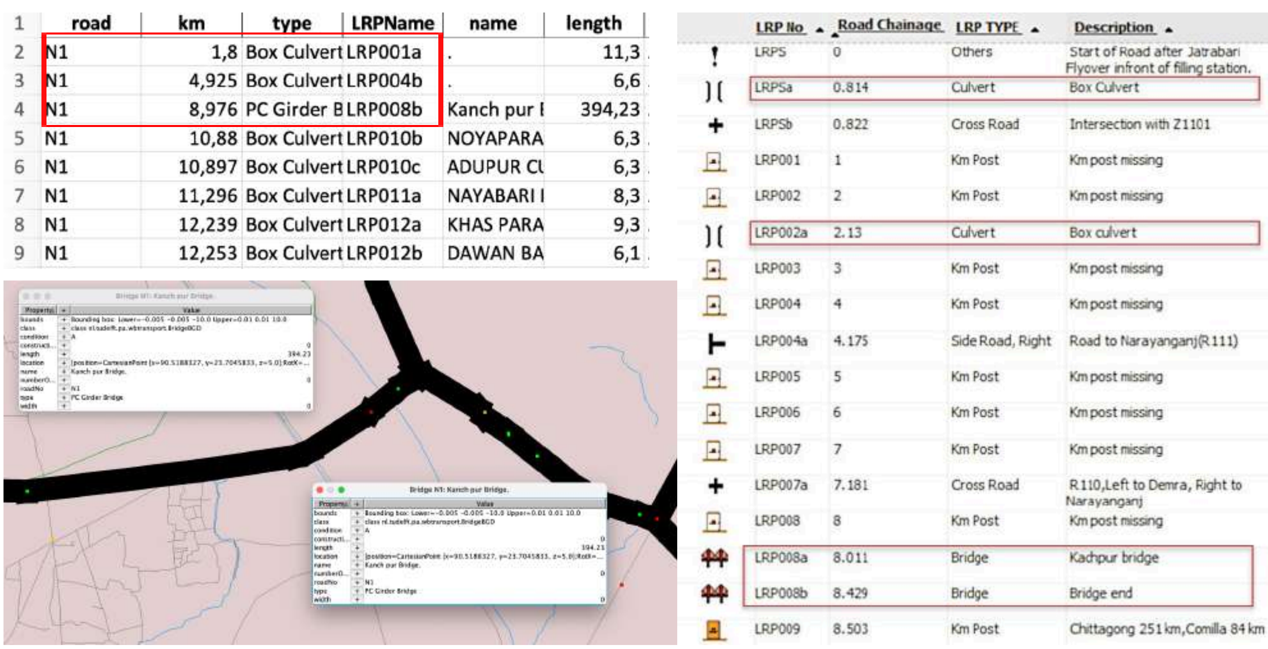
Inconsistent Widths of Waterways

Some rivers show a different path in the data than in the real world. For instance, the Baral river in the West of Bangladesh is not properly continued in the data.

Figure 17: *Error Example of inconsistent waterway*

3.2c Semantic Inconsistency

As the data was collected by several divisions within the Ministry of Transportation, inconsistent key values (i.e different LRPs for the same bridges) within the RMMS and BMMS data were used. The heterogeneity of this convention causes bridges to be represented twice.



1	road	km	type	LRPName	name	length
2	N1	1,8	Box Culvert	LRP001a	.	11,3
3	N1	4,925	Box Culvert	LRP004b	.	6,6
4	N1	8,976	PC Girder B	LRP008b	Kanch pur I	394,23
5	N1	10,88	Box Culvert	LRP010b	NOYAPARA	6,3
6	N1	10,897	Box Culvert	LRP010c	ADUPUR Cl	6,3
7	N1	11,296	Box Culvert	LRP011a	NAYABARI I	8,3
8	N1	12,239	Box Culvert	LRP012a	KHAS PARA	9,3
9	N1	12,253	Box Culvert	LRP012b	DAWAN BA	6,1

LRP No	Road Chainage	LRP TYPE	Description
LRPS	0	Others	Start of Road after Jatrabari Flyover infront of filling station.
LRPSa	0.814	Culvert	Box Culvert
LRPSb	0.822	Cross Road	Intersection with Z1101
LRP001	1	Km Post	Km post missing
LRP002	2	Km Post	Km post missing
LRP002a	2.13	Culvert	Box culvert
LRP003	3	Km Post	Km post missing
LRP004	4	Km Post	Km post missing
LRP004a	4.175	Side Road, Right	Road to Narayanganj(R111)
LRP005	5	Km Post	Km post missing
LRP006	6	Km Post	Km post missing
LRP007	7	Km Post	Km post missing
LRP007a	7.181	Cross Road	R110,Left to Demra, Right to Narayanganj
LRP008	8	Km Post	Km post missing
LRP008a	8.011	Bridge	Kachpur bridge
LRP008b	8.429	Bridge	Bridge end
LRP009	8.503	Km Post	Chittagong 251 km,Comilla 84 km

Figure 18. *Error of Inconsistent Use of Key Values*

3.2d Summary of Data Quality Issues

Altogether, we have identified 13 data quality issues across all categories and criteria displayed in Table 1.

Table 1. *Table of Data Quality Issues by Category and Criteria*

<table>
<tr><th>Data Category</th><th>Criteria</th><th>Data Quality Issues</th></tr>
<tr><td rowspan="2">Syntactic</td><td>Accuracy</td><td>Null Values Instead of Numerical Data</td></tr>
<tr><td>Consistency</td><td>Road Naming Convention</td></tr>
<tr><td rowspan="3">Semantic</td><td>Accuracy</td><td>Lat and Lon Errors
Location of Bridges
Inaccurate Length of Bridges
Duplicate Bridge & Road Entries
Intersection Issues</td></tr>
<tr><td>Completeness</td><td>Missing data:
Construction Years
Bridge Names
Length of Bridges
Bridges
Width of Waterways</td></tr>
<tr><td>Consistency</td><td>Different data keys:
Inconsistent LRPs for Bridges</td></tr>
</table>

3.3 Pragmatic Data Quality Issues

The pragmatic dimension considers the context in which information is used and the effectiveness of its communication, including pragmatic **completeness** (Wang and Strong, 1996), **timeliness** (Wang and Strong, 1996; Price and Shanks, 2005), and **presentational suitability** (Price and Shanks, 2005; McGilvray, 2008). To simplify matters, we will not differentiate between those criteria. Instead, all previously identified data quality issues will be assessed according to our use of data; and hence will be subject to our information judgment. To operationalize this assessment we identified three key factors relevant to our purpose:

- Correct LRP for Roads and Bridges
- Number of Bridges
- Length of Bridges

We will use the road and bridge data to build a model to simulate good transports. Hence, we need accurate and complete road and bridge data. To ensure that, we define all data quality issues related to LRP errors for roads and bridges as pragmatic. Additionally, data quality issues concerning the accurate amount and length of bridges are important for later assessment - the amount of destroyed bridges causes travel delay (sensitive to bridge duplicates); the length of bridges determines the exact delay time for each bridge (assignment 2).

The following data quality Issues have been identified as pragmatic quality issues.

E1) Lat and Lon Road Errors

E2) Location of Bridges

E3) Intersection Issues

E4) Inaccurate Length of Bridges

E5) Missing Length of Bridges

E6) Missing Bridges

E7) LRPs for Bridges

E8) Duplicates of Bridges & Roads

4. Prioritization

We identified seven pragmatic issues with data quality. Due to the scope of the project and time constraints, six issues have been addressed. The documentation can be found in Section 5. These six issues were selected according to two main prioritization criteria - derived from the research questions.

- **Importance**: To what extent will this data quality issue jeopardize the validity[1] of the simulation model?

- **Solvability**: Are there scientifically accurate and viable (within the scope of this project) means to deal with the issue?

The combination of solvability and importance highlights which issues are a priority for the purpose of the simulation (Figure 19). Due to the scope of the project, a qualitative assessment of both importance and solvability was developed using three categories for each criterion (low, mid, and high).

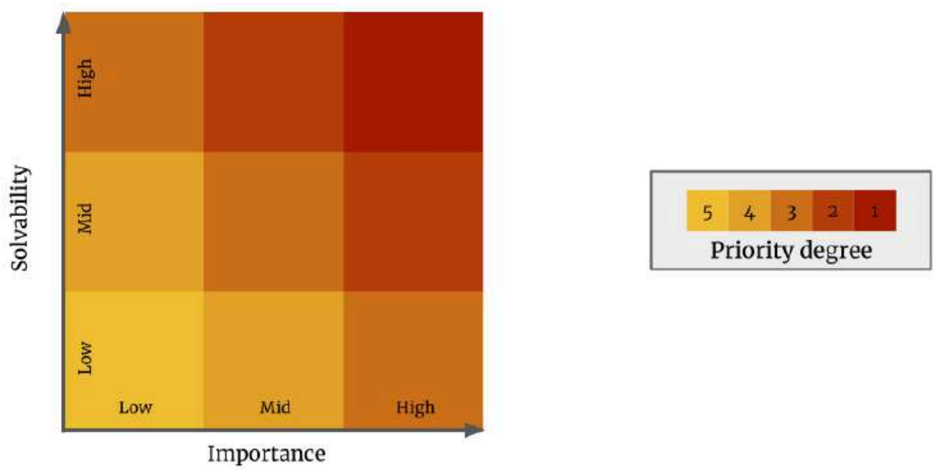


Figure 19. Prioritization Matrix of Importance and Solvability

[1] Model validity is associated with the extent to which a model is suited for its intended purpose. In this case, it refers to what extent our model enables us to estimate the criticality and vulnerability of natural hazards of Bangladesh's transport infrastructure

4.1 Importance

The process to assess the importance of the data quality issues was derived from the research question and the objectives of future assignments, as mentioned in Section 3.3. These criteria consider the role the infrastructure with each issue has on the overall **criticality** and **vulnerability** of the road infrastructure.

A quantitative assessment of criticality was conducted for all the pragmatic errors identified. Conversely, vulnerability can be readily assessed using the information available in the dataset by using the bridge conditions rating. However, since it is a measure that is only present for bridges and not roads, the vulnerability assessment was excluded from the qualitative model for issue prioritization.

Criticality

The main infrastructure types used to assess critical infrastructure are roads, bridges, and intersections. Within each infrastructure category, we divide and order them into subcategories according to the level of importance in our model due to the geographical context (Table 2).

- **Road type**: National roads are prioritized, followed by Regional and Zila roads. This follows the hierarchy of road classification, where they are in descending order of mobility and economic impact.
- **Road length**: Longer roads are prioritized. Side/short roads will eventually be eliminated as it is not as useful in understanding nationwide connectivity.
- **Bridges**: Longer bridges are more important because they have greater delay time.

Table 2. Level of Criticality for Different Infrastructure Types

	Low	**Mid**	**High**
Road type	Zila	Regional	National
Bridges	S bridges (under 10m)	L and M bridges (10 - 200m)	XL bridges (over 200m)
Road length	<25km	25<x<100km	>100km

4.2 Solvability

Solvability will be assessed by **computational complexity** and **accuracy of solution** and **quantity of errors**. This is largely a technical assessment, illustrated in Table 3.

- **Computational complexity**: Most solutions require a filtering algorithm or/and operations. They vary in the ease of solving based on the required algorithms' complexity level.
- **Accuracy of solution**: Solvability would be dependent on the extent that a low uncertainty solution can be implemented. Solutions might not be able to address the problem space comprehensively - they might miss out on some errors or even create new ones.
- **Amount of data points**: Lastly, the solvability of error would depend on the size of the error space.
- **Resources needed:** Finally, the errors requiring external sources, such as GIS analysis, will have lower solvability than those that don't require any additional data or calculation

Table 3. Level of Solvability

	Low	Mid	High
Computational complexity	Complex computation structures (nested loops, array calculations, etc.)	Simple processes with unknown indexes	Simple processes with known index
Accuracy of solution	Errors addressed with high uncertainty	Errors addressed with mid uncertainty	Errors addressed with low uncertainty
Amount of data points	>500	10<X<500	<10
Resources needed	No calculation or additional data is needed	Computing using the dataset values is needed	Secondary resources are needed (eg. GIS software)

4.3 Assessment of Errors

This section presents the results of the prioritization of the data quality issues using the importance and solvability criteria (Figure 20). Of the seven pragmatic issues identified in Section 3.3 - three were identified with the greatest priority (Priority Level one; E1, E2, E8) and thus were selected to be implemented as described in Section 5. For accountability, the assessment of the other errors is qualitatively described in Table 4.

Table 4. Issue Assessment and Priority Level

Priority Level 1
E1) Lat and Lon Road Errors are very important to determine the road network structure in our critical assessment; solvability is fairly doable with interpolations and direct adjustment of specific road point coordinates.
E2) Location of Bridges is very important in our criticality and vulnerability assessments; solvability is relatively easy as we can use the coordinates of the road LRPs to either find the exact location or otherwise interpolate the bridge coordinates.
E8) We assume that duplicates of bridges & roads greatly impact the outcome of future model simulations. Furthermore, it causes data redundancy, making data management more difficult and time-consuming.
Priority level 2
E4) The time delay for destroyed bridges is influenced by the bridge length and can be measured using an interval scale. Using an interval scale to measure delay time means that the relationship between delay time and bridge length is not necessarily linear, and hence small differences in bridge length may not necessarily result in a corresponding difference in delay time.
E5) Lengths of bridges are useful for the computation of criticality as it influences delay time; solvability is moderate - there are means to reference other datasets and calculate the lengths of each bridge.
E6) Missing bridges will be important in assessing vulnerability; Solvability is limited as we would need to use external sources and cannot algorithmically assess the missing bridges.
E7) Consistent names for Bridge LRPs are important to identify respective LRPs and spot potential duplicates clearly; Solvability is limited by first finding potential naming rules and then adjusting all cases.
Priority level 3
E3) Intersection Issues are highly important to determine the road network structure used in the criticality assessment; solvability is rather low because of how the issues are "case-by-case" where manual assessments are necessary. Solutions also ideally need to have high accuracy due to their importance.

As a result, we intend to address issues with a priority degree of one; hence we omit E3, E4, E5, E6, and E7 due to lower priority degrees.

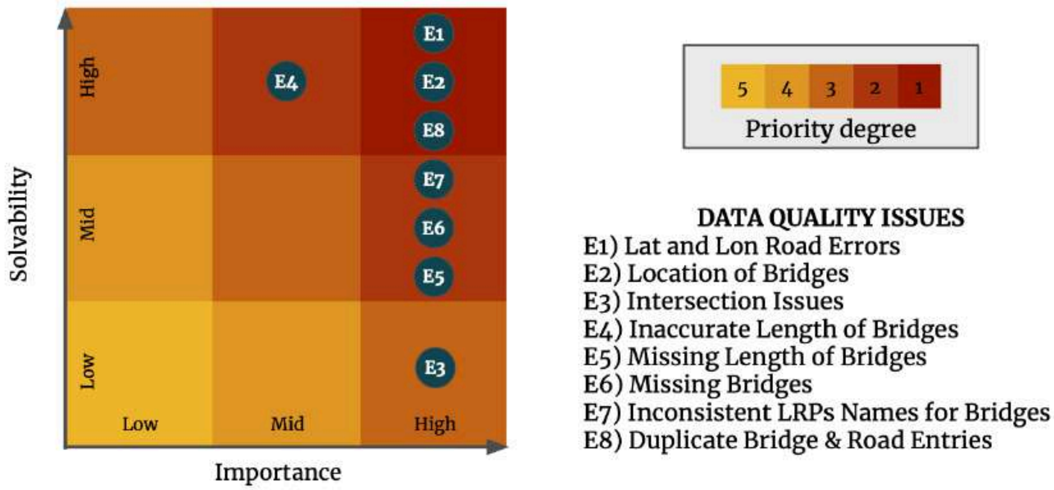


Figure 20. Qualitative Estimation of Priority Degree Considering the Importance and Solvability Criteria

5. Implementation

For solving the identified data quality issues, we applied a stepwise approach. First, we cleaned the road dataset and afterward applied necessary changes to the bridge dataset with the given cleaned road data. We implemented the solution in two separate python files and modularized every step as a separate function to ensure readability. Furthermore, we solved each aspect in a separate function to make the process modular and interoperable. Moreover, we aimed to provide generalizable code that can be used for further analysis of the same data set or could be easily adapted to solve similar issues in various other data sets. This also facilitated the stepwise approach, as we could easily test individual functions and see how much they would change the network.

5.1 Cleaning of Road Data Addressing E1

First, we read all files of the provided raw data RMMS folder and looped through each road LRPs overview file. We extracted the information of all LRPs of the respective road, including the chainage using create_list_of_road_records(file) for every road. All this information was locally cached in memory to run our cleaning algorithms.
All errors were addressed in separate methods to ensure readability and test different cleaning process stages. With this modular approach, we could assess the efficiency and importance of different error types and see the impact of each change.

Duplicate Road Points Addressing E8

First, we carefully addressed duplicate values in the remove_duplicates(rr_list) function. In our solution, we ensured that these points were truly duplicates and removed the second entry from the data set to decrease the data set size and provide an accurate infrastructure representation. We assumed that we could remove road points that have the same LRP, the same coordinates, or the same chainage values. If the type and name differ between these road points, we added that information to the remaining road point.
We ran all cleaning steps in multiple iterations to see the effect of each step and assess if further steps were necessary. In this step, we were able to adjust 619 duplicates.

Correction of Start Points

We have found some typos in the start values for road entries. As our following algorithms expect these values to be accurate, we had to adjust them individually. These streets were visually identified and then fixed in correct_road_start_points(rr_list) by adjusting latitude or longitude by +/- 1, depending on the respective case.
Doing so could fix the start points for 8 roads, including one National road. Visually, these changes could be seen as some roads were previously outside Bangladesh and after the cleaning at their respective position inside Bangladesh, e.g., Z3711.

Chainage Fixes

As a next step, we tackled the spikes inroads that could be linked back to inaccurate coordinates that were not adequate to the chainage. We assessed the values and acted based on the quotient and thresholds by adjusting the latitude and longitude of a point by an average of the previous and consecutive points.
The used thresholds ensure that only points in a feasible range are adjusted. If points were further off, taking the average would not be as effective as the extreme values would shift the interpolated coordinates. A point is adjusted if the quotient of distance and chainage between points is higher than 1.2, meaning that the distance is at least 20% off the chainage.
This way, we addressed 1101 road points. Visually, we saw that most spikes in roads were adjusted (See Figure 21).

Remaining Outliers

Given our previous steps, we noticed that there were a few remaining spikes in roads visible in the visualization. After looking into specific examples, we saw that it was a typo in either the latitude or longitude, e.g., 22 instead of 23.
We assumed that the starting point of a road point should be most likely at accurate coordinates, especially after our previous adjustments, leading to the following approach to solving the issue in fix_chainage(rr_list).
Based on the assumption of correct coordinates for the first point, we claim that the coordinates of the following road points cannot be off by more than an absolute value of 0.5, which would be a distance of 55km. In doing so, we adjusted 448 road points. Visually, we see tremendous differences between the initial and current data sets.

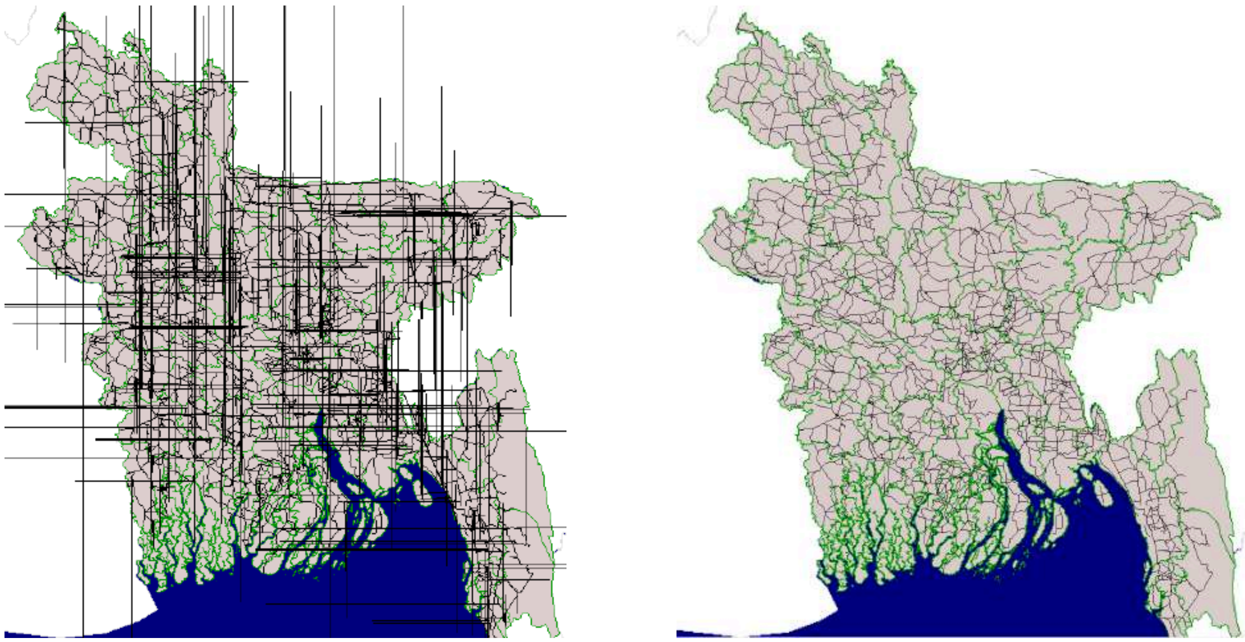


Figure 21. Comparison of Road Networks Prior(left) and After(right) Cleaning Steps

Writing to Files

Based on the cleaned data sets, we wrote the data back to the appropriate files. We wrote the data back to a tab-separated values file for the roads with the same formatting as the original _roads.tcv using the python built-in functions.

5.2 Cleaning of Bridge Data Addressing E2

With the cleaned road data, we could now adjust the bridge information by running the fix_bridges.py script. We looped through the provided bridge_overview.xlsx of the BMMS folder and checked if the chainage of a bridge is accurate to any chainage value of the bridge. If not, we interpolate the bridge's location by using the previous and consecutive points. We adjusted the position by using the ratio $\frac{(chainage_{Next} - chainage_{Bridge})}{(chainage_{next} - chainage_{previous})}$. This way, the location was adjusted by using the chainage values and ensured that chainage and coordinates are aligned.

This method introduces uncertainty as we calculate the position of bridges based on the corrected location of roads that already have a level of uncertainty in operations, e.g., the correction of typos in the coordinates.

Writing to Bridge File

The cleaned bridges were written to BMMS_overview.xlsx with the same table structure. This way, we ensured we could run the simulation after each iteration.

5.3 Testing of New Files

As a final step, we used our updated road and bridge files and visualized them using the provided java program. The difference between the initial and the cleaned data set can be seen below.

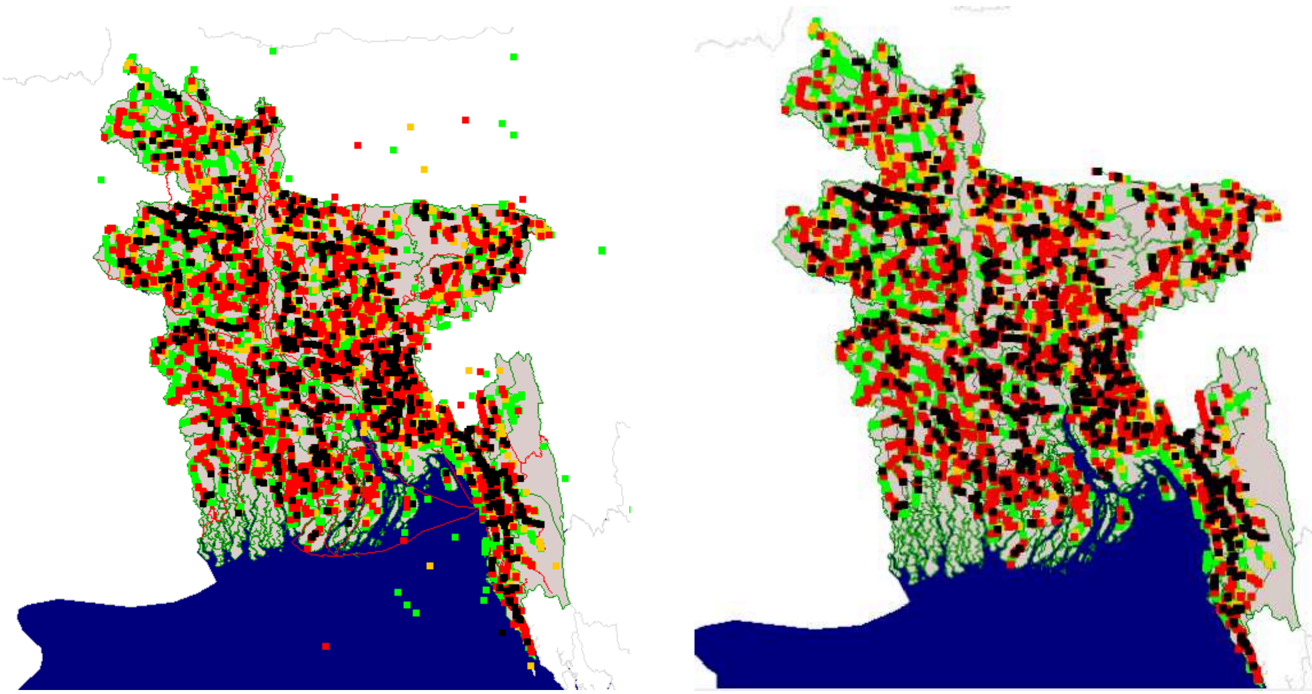


Figure 22. Comparison of Transport Network Prior(left) and After(right) Cleaning Steps

6. Discussion and Reflection

Our report provides a general strategy for addressing data quality issues and furthermore, illustrates how these ideas were implemented in the case of transport infrastructure data in Bangladesh. With the implemented measures, we took the first steps towards improved data quality in the present data sets. By doing so, we can improve our decision-making by achieving higher accuracy in simulation models.

Limitations

Our current analysis and implementation were done with limited time and resources. Hence, we are aware of multiple limitations and also see potential improvements. The available data sets are not complete as we miss data on some smaller roads and also new constructions. Moreover, no information about the railway system was used which could serve as an interesting alternative form of transport in future simulations. Due to the limited time, we only focused on pragmatic issues that would also have a significant impact on future analysis.

Our approach is also limited by how one defines good data quality. It is limited to the objective view of quality based on the stored data's fidelity to the represented external world (i.e. not on data use) (Wand & Wang, 1996). In this regard, there is also an overlap in data quality categories and their criteria, which creates some ambiguity in how data quality is assessed.

Improvements

Moving forward, one could improve the data quality with multiple additional steps. We could utilize external sources like GIS - to receive more accurate information about roads and infrastructure for cross-referencing. In addition, one could also use information from, e.g. OpenStreetMaps, to update the street and bridge network. In our current approach, we have not analyzed the waterway data, yet, given more time and resources, it could be interesting to have an additional analysis and clean-up process on this layer as it can influence key characteristics of roads and bridges.

Extensions

We could also establish a better way of tracking the progress of data cleaning. In this report, we scoped down to a subset of data quality issues. If we intend to tackle all of them, we would need to establish a robust set of rules (per data category and criteria) to quantitatively assess the quality of data.

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Report Assignment 2

Component Building Model Generation & Simulation

EPA1352: Advanced Simulation

"That's some insane chainage" - Ariel Goldin

March, 2023

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1 Introduction

Bangladesh's high population density and geographic location make it highly vulnerable to natural disasters. The country is mainly located in the delta of the Padma and Brahmaputra rivers resulting in a high density of waterways. Due to this topography, the transport infrastructure comprises many bridges, some stretching up to six km long. These bridges act as bottlenecks in the transport network. The national road N1, which runs from Teknaf in the south to Tetulia in the north, is highly critical to the country's economy as it connects major cities and districts. To assess Bangladesh's vulnerability, understanding the effects of bridge maintenance and its unavailability due to natural hazards is crucial. Hence we ask:

> Q1) How does the unavailability of bridges of the N1 between Chittagong and Dhaka affect the average travel time?
>
> Q2) The unavailability of which bridges have the biggest impact on travel time, and hence are the most critical ones?

To answer these questions, we adjusted the agent-based BangladeshModel, representing trucks driving on the national road N1 from Chittagong to Dhaka. To assess the average travel and delay time, several scenarios are simulated. In the following chapter, the methodology is described. Afterwards, the results are presented. In the end, we discuss the results and limitations.

2 Methodology

The overall workflow for this report is displayed in Figure 1. First, we analyze the component structure of the mesa model Bangladesh_Model to deepen our understanding of the demo model. Based on that understanding, we adjust model components relevant to the scenario testing. Furthermore, a data collector is implemented that exports the generated simulation data. Then the input data is cleaned and prepared for use in the model. After the simulation, we analyze and discuss the output data.

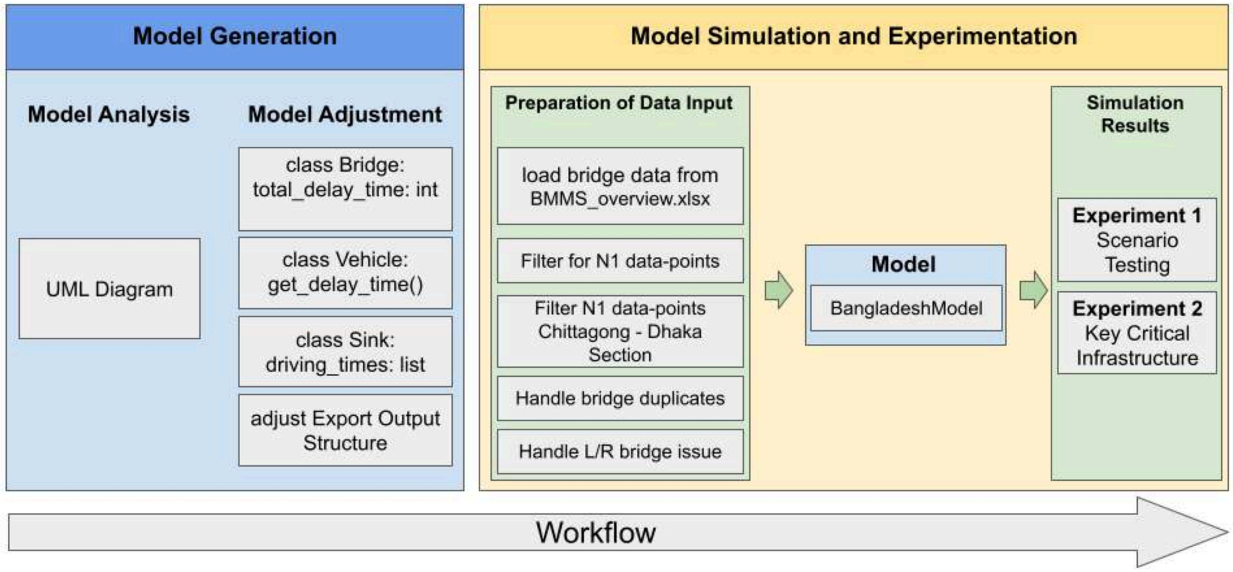

Figure 1. Flow Chart Diagram - representing the steps taken to answer the research questions

2.1 Model Generation

Model Analysis

The agent-based BangladeshModel used for answering the research questions is a component-based model. A component is a unit in the model that encapsulates its internal structure and interacts with its environment through interfaces (Verbraeck & Dahanaya, 2002). For many reasons, this modeling type is used for managing complexity and enhancing reuse (Hofmann, 2004).

Because it is difficult to provide a clear overview in the text of the different components and the relationships between them, a UML diagram is instead used (Figure 2). UML diagrams are widely used to visualize model components and can also be valuable for providing insight into ABM models (Bersini, 2012).

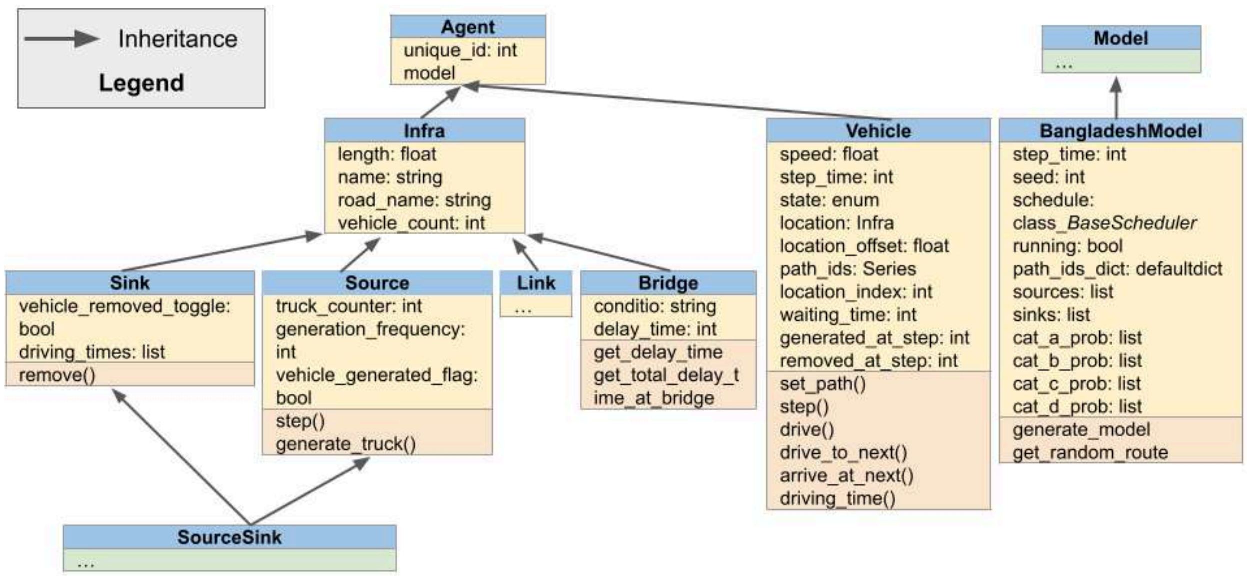

Figure 2: UML of the Transport Infrastructure Mode. Blue background indicates component names. Yellow background represents component attributes. Orange background illustrates the component methods. Green background displays that no attributes, or functions are defined.

Model Adjustments

In the recent updates to the model, we made changes to the way it handles certain classes:

- For the **Vehicle class**, we introduced a **new method** called "**driving_time()**" that calculates the time it took the vehicle to reach the destination as it was seen as an important variable that needs to be repeatedly computed.

- For the **Bridge class**, we added a **new property** called "**total_delay_time**", an integer that represents the total amount of time that vehicles are delayed because of the bridge. To support this change, we also adjusted the **"get_delay_time" method,** which calculates the delay time for a single vehicle, to consider the probability of a bridge breaking down.

- Additionally, we modified the **"init" method** of the **Bridge class** to ensure that the delay time property is initialized based on the bridge length. This way, we collected the total delay time for each bridge which helps us to assess which bridges are the most critical ones.

- Finally, we added a **new property** to the **Sink class** called "**driving_times**". This list contains the driving times for all the vehicles that have reached the sink. The model output then computed the list and saved to the related scenario output csv. Thereby, we can save and export the model output.

Export Output Data Structure (Bonus)

In earlier model runs, it was observed that many of our export functions were cluttering the model_run.py file. Hence, we decided to not use Mesa's dataCollector and create our own collector following a model component design approach. Thus, we introduced a ***ModelOutput*** **class** for a model run that collects all relevant information and provides methods to display and export data. By doing so, we capsulated the logic and provided a module that could easily be reused, and we can extend it for additional analysis (Lau et al., 2007). Moreover, it provides another layer to the program as import, processing, and export are clearly separated.

2.2 Preparation of Input Data

In a Jupyter Notebook we used the provided bridge data in BMMS_overview.xlsx and filtered only to include entries on the road "N1". Moreover, we removed entries that are not between Chittagong (LRP235b) and Dhaka (LRPS) by looking for a chainage smaller than 232.754.

As there can be multiple entries that direct to the same bridge or different parts of a bridge (e.g. left and right side), we decided to merge these entries together and take the average length and the worst condition. In this way, we simplified the analysis while following a conservative and more robust approach. We linked the bridges with "link" type entries whose length was a result of the chainage of the following bridge and subtracted from the length of the current bridge and its chainage. Afterwards, we added a first entry as 'source' and a last as 'sink'. Eventually, we exported the data infrastructure.csv with the predetermined column headers to make it readable for our model.

2.3 Scenario Definition

The BangladeshModel is used to generate eight scenarios. This way, our assessment of resilience can become more robust and reduce uncertainty. By having ten iterations for each scenario with a different random seed, we address the issue of stochasticity. The scenarios vary in their probability of a bridge breaking down (Figure 3). Furthermore, we collect the total delay time for every bridge to analyze the most vulnerable bridges. The length of each bridge defines the range of predefined delay times (Table 1).

In each scenario, a truck is generated every 5 minutes by a source, at the start of road N1 (Chittagong, LRP235b). The trucks drive at a speed of 48 km/h. The model runs in steps, with each step accounting for one minute. With the N1 being 232,75 kilometers in length between Dhaka and Chittagong, it would take an average of 4:52 hours (Table 2: Scenario 0).

Table 1: Bridge Delay Time

Bridge length	Delay time for a truck
> 200 m	Triangular(1, 2, 4) hours
50 - 200m	Uniform(45, 90) minutes
10 - 50 m	Uniform(15, 60) minutes
< 10 m	Uniform(10, 20) minutes

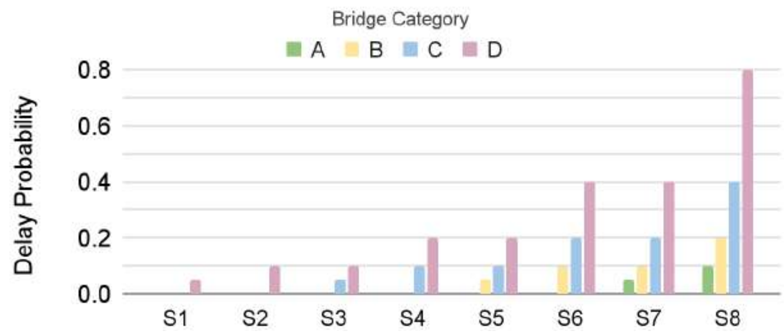

Figure 3: Bridge Scenario and Delay Probabilities for Bridges

3 Simulation Results

3.1 Experiment 1: Scenario Testing

Comparison Between Scenarios

Before simulating the scenarios, we hypothesized that the total driving time would increase from scenario one to eight since they are implicitly ordered (descendingly) based on the severity of damage to bridges (Figure 3). This hypothesis is confirmed. Table 2 shows that in scenario 0, where there are no damaged bridges, the average travel time per scenario is 4 hours and 52 minutes. With each successive scenario, the average time increases. In scenario 8, the average travel time is more than quadrupled compared to the base scenario 0.

Table 2. Average Total Travel Time per Scenario

Scenario	0	1	2	3	4	5	6	7	8
Time [hr:min]	4:52	4:56	4:59	6:16	7:07	8:23	10:56	12:00	20:25

In addition, the individual travel time of agents presents a larger variation concerning the mean in the scenarios that have larger waiting times (Figure 4). This effect is consistent with the higher probabilities of larger delays for the more extreme scenarios. The effect can be explained by the fact that in more extreme scenarios, the chance that the average travel time for a specific scenario deviates far from the mean is greater.

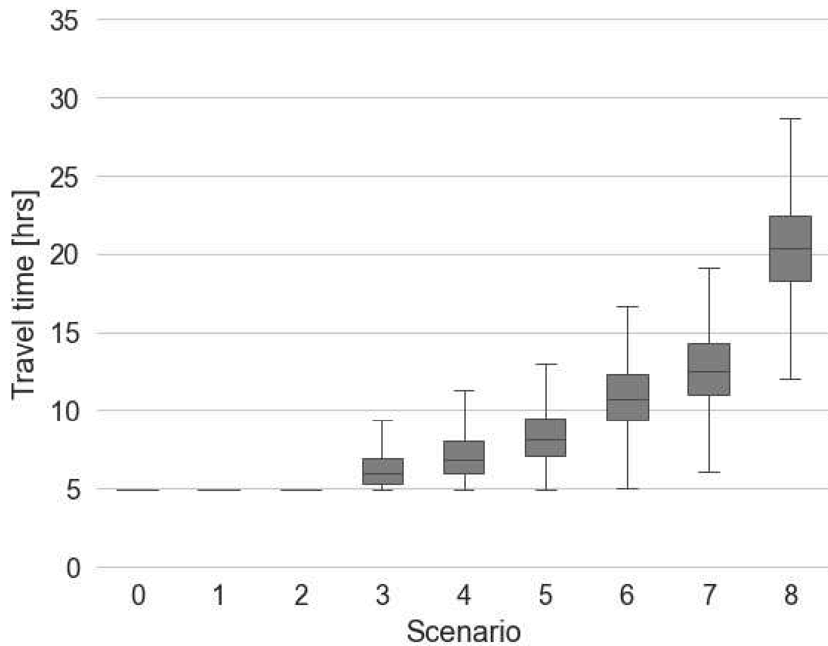

Figure 4. Driving Time Distribution per Scenario

Comparisons Between Iterations

For each scenario, ten iterations were performed with different random seeds. To assess if stochasticity impacted our results, we compared the distribution of the driving times for each iteration for every scenario. Each iteration results in similar distributions and overlaps (Figure 5). Thus, the random seed stochasticity has minimal impact on our model's estimations of travel times.

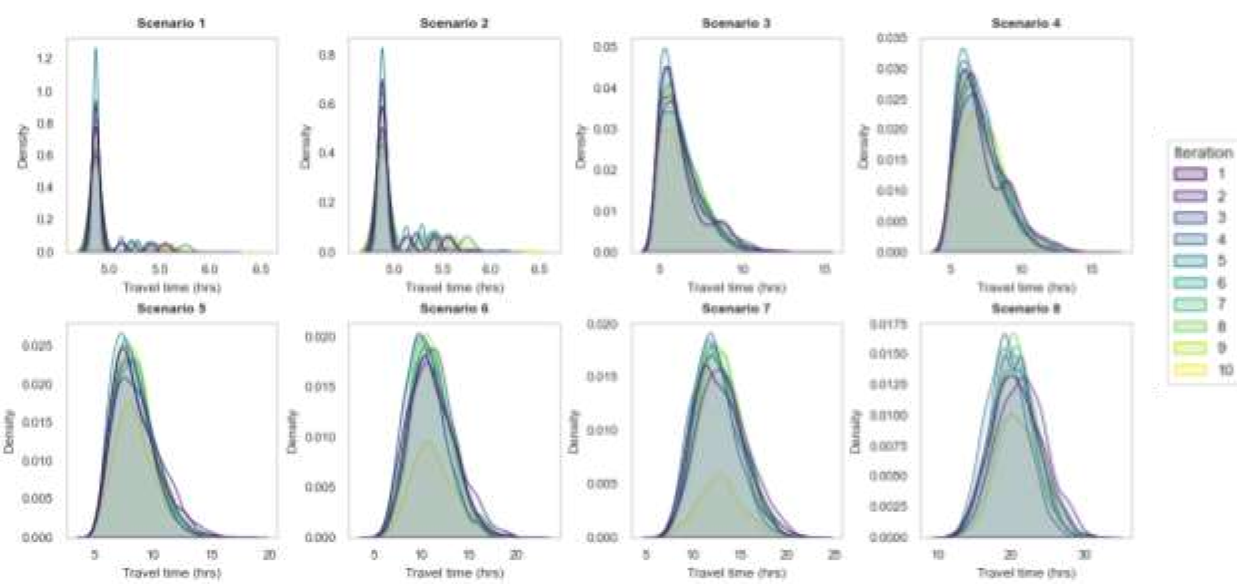

Figure 5: Stochasticity Assessment per Scenario

3.2 Experiment 2: Key Critical Infrastructure (Bonus)

As a second analysis, we collected the delay time that each bridge is responsible for and took the average across scenarios. The five bridges with the highest average delay time across the scenarios are in bad condition (conditions C and D) and have a relatively great length (Table 3).

Table 3: Bridges and their Average Delay Time

Bridge Name	**Condition**	**Length [m]**	**Rounded Average Delay Time [min/vehicle]**
Kanchpur Girder Bridge	C	397	27
Daud Kandi Bridge	C	1408	23
Meghna Bridge	C	900	23
Modonhat Bridge	D	24	16
Langalbandh Bridge	C	99	13

Figure 6: Google Street View from Kanchpur Girder Bridge, the bridge with the highest average delay time.

For the most critical bridge, a vehicle would, on average, be delayed by 27 min across all scenarios. This information can be of great value for the Bangladeshi government when deciding on infrastructure works to increase the resilience of its infrastructure and reduce economic damage. The importance is acknowledged by the Bangladesh government, as in recent years, they increased maintenance work for critical bridges (i.e., for the Kanchpur Grider Bridge, Daud Kandi Bridge, Meghna Bridge, and Langalbandh Bridge (BSS, 2021; Modena, C. et al. 2012; UNB, 2019;)).

4 Discussion and Limitations

Results Discussion

Summary of Key Observations
• Importance of bridges can be observed by the exponential increase in travel time in relation to the worsening scenarios • Critical Bridges are: 3 Long Bridges (>200 m), 1 Medium Bridge (~100 m) and 1 Short Bridge (<20 m) • Government has identified importance of critical infrastructure points as most of the bridges we found to be critical are already under maintenance.

In our agent-based model, we observe how the infrastructure changes have produced an emergent outcome of the road system in the form of delay time. Our experiments were intended to assess the vulnerability and criticality of the infrastructure. In Experiment 1, we used scenarios to understand the impact of bridge conditions on vehicle travel time; in Experiment 2, we determined the most critical infrastructure.

There are assumptions in the way we model vehicular movement. We set a constant speed and did not model any vehicle-to-vehicle interaction (congestion). The bridges were also simplified, where we combined the parts of the bridge (left and right) into one appropriate for the aggregation and scoping of the model. There is also no real-world data to test the assumption of bridge damage percentage.

Stochasticity

The results of Experiment 1 on the total travel times showed negligible sensitivity to the stochasticity of the current model. In addition, we did not conduct an assessment of stochasticity for Experiment 2 since the space for randomness for the current model is insignificant as there is just one source and sink and one road (N1).

However, we assume that future models representing a more complete transport infrastructure and more complex traffic behavior can become more sensitive to randomness; and hence more comprehensive assessment of the stochasticity would be required to increase the robustness of the results.

Scalability

Scalability is a significant design concern as it is assumed that this lab practice is to prepare us for the other assignments that use more of the street network with more experiments and scenarios. We accounted for this by 1) preparing the algorithm to manage a bigger street network. For instance, instead of hardcoding data collection from the specific sink and source, our algorithm iterates through all of them as it is anticipated that more sinks and sources will be used in future lab assignments. 2) designing the components with modularity in mind, so it would be more organized to add more functions. For instance, the ModelOutput class was created to expand data collection functions easily.

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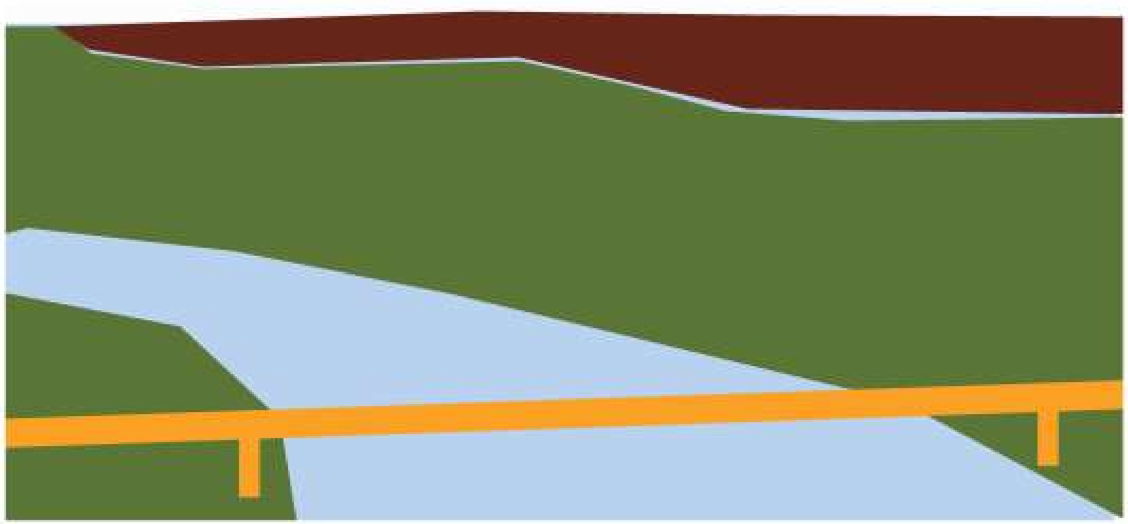
Report Assignment 3

Multimodal Approach Generation & Simulation

EPA1352: Advanced Simulation



24 March, 2023

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1. Introduction

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 studies this model by expanding on the multimodal approach and integrating a Network Model into the Agent-Based BangladeshModel. To assess Bangladesh's vulnerability to disruptions in the transport infrastructure, we perform a simulation experiment that investigates five different scenarios. Within these scenarios, we investigate:

Q1) How does the unavailability of bridges in the current Transport Network affect the effective travel speed?

Q2) Which bridge characteristics have the biggest impact on travel time?

1.1 Model Description

In the current iteration of the BangladeshModel our transport infrastructure has grown from solely analyzing the N1 to studying both the N1 and N2 and the major side roads that intersect with them (National roads that are longer than 25 km). Thus, the complex model now represents links, bridges, and intersections. Moreover, every endpoint of the transport network can now generate and remove trucks; hence our current model iteration accounts for both ways of travel.

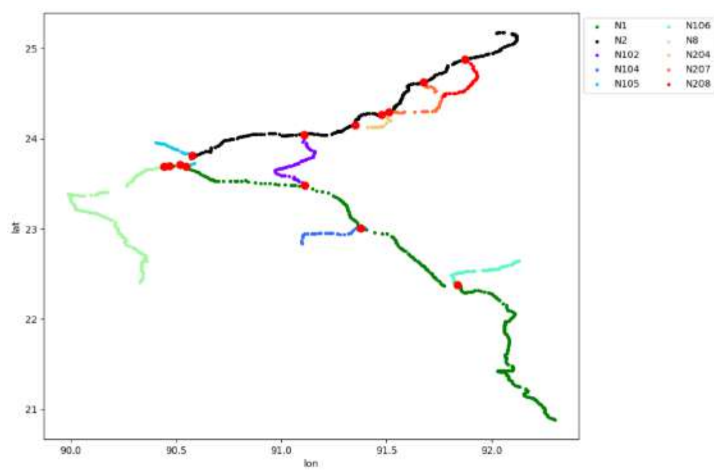

Figure 1. Representation of the current transport network

1.2 Model Objectives and KPIs

The criticality of transport infrastructure highly depends on the deployed metrics. Jafino et al., identified 17 different transport metrics, illustrating the various perspectives one can take to assess the criticality of transport infrastructure (Jafino et al., 2020). Therefore, one always has to consider the purpose of the experimental setup and choose criticality metrics, respectively. For the current BangladeshModel generation, we have the following objective:

> Develop a multimodal approach that integrates Agent-Based and Network modeling to analyze the network's travel time and study each scenario's effects on the travel time.

Table 1. KPIs selected to inform bridge criticality

Title	Definition	Aggregation
Total Delay Time (TDT)	$TDT(S_n) = Delay\ time$ Where m represents each bridge and n varies from scenario 0 to 4	local
Average effective speed (AES)	$AES(S_n) = \sum_{m=1}^{28,800} \frac{Traveled\ distance_m}{Travel\ time_m} / 28,800$ Where m represents each truck and n varies from scenario 0 to 4	Network-wide

Note. The aggregation dimension is derived from Jafino et al. (2020).

The TDT estimates how much a particular bridge would contribute to the overall delays in the network. The AES calculates the average speed at which the cars move in the network considering the delays experienced in the bridges. Both TDT and AES are related to criticality metrics that can be categorized as *utilitarian* metrics of *accessibility* following the framework introduced by Jafino et al. (2020). These KPIs differ on the aggregation dimension, as shown in Table 1.

2. Model Generation Methodology

2.1 Data Preparation

To construct the NetworkX model, the transport infrastructure has to be converted to nodes and links. We have defined four types of nodes: sourceSinks, links, bridges, and intersections. The intersections are the only elements not readily defined in the cleaned data set we produced in previous assignments. To identify the location of these intersections, we have implemented and combined two methods as described in the following subsections.

2.1.1 Intersection Identification Method

<u>1) Filter out roads shorter than 25 km</u>

The N Roads data are filtered by length using the *chainage* values provided. The remaining roads, except N1 and N2, are *other roads*.

<u>2) *Find_intersections*: Searching for potential points in N1 and N2 as intersections</u>

All points in N1 and N2 are looped through and compared with the points in every *other road* longer than 25 km. If the points are within a certain threshold distance, the point in N1/ N2 will be considered a potential intersection. For simplicity, the intersection point on the *other road* will assume the position of this intersection point in N1/N2 as it is very likely (as seen from LRPs) that the intersections are usually collected as points on major roads. Also, the threshold distance was calibrated to obtain the most accurate intersection results.

<u>3) *Remove_intersection_duplicates*: Removing duplicates representing the same intersection point</u>

Then, all potential intersections are looped through with a certain threshold distance; if two intersection points are close, they are assumed to represent the same intersection, and the one closer to the *other road* will be taken. The difficulty of this step lies in creating exceptions to prevent wrong deletions. For instance, as depicted in Figure 2 (center), two points might be extremely close to each but are intersections with different roads.

2.1.2 Cross-Referencing Dataset with OSMnx Dataset (*BONUS)

The OSM road network data (OpenStreetMap, 2017) provided in Assignment 1 was useful in improving data accuracy through cross-referencing. The OSM road network has line vectors with the data *osm_id*, *name*, and *type*. However, none of this was useful in referencing the infrastructure data we have that is identified by *road* and *name* (in a different naming convention). As such, the only useful aspect of being compared is geometry; in other words, we can check OSM if an intersection exists but not if it is the same/correct intersection between two roads. Its utility will be limited to validating the intersections identified but not the ones missed (Table 2). Hence, the OSM data will not be used as a part of the algorithm but only for an accuracy test.

Table 2: Confusion Matrix - Teal-colored cells represent the areas our cross references can account for, which validates the intersections we have identified but validates the intersections we did not identify.

		OSM Data	
		True	False
LRP data-set intersection identification	True	True Positive	False Positives
	False	False Negatives	True Negatives

We studied this qualitatively and visually using QGIS (QGIS.org, 2022). A 3km radius around the intersection was then drawn as a tolerance boundary and visualized alongside the OSM network data and OSM map overlay (Figure 2). It is then analyzed 1) if the intersection identified truly exists (true positive rate) and 2) if the intersection is spatially accurate.

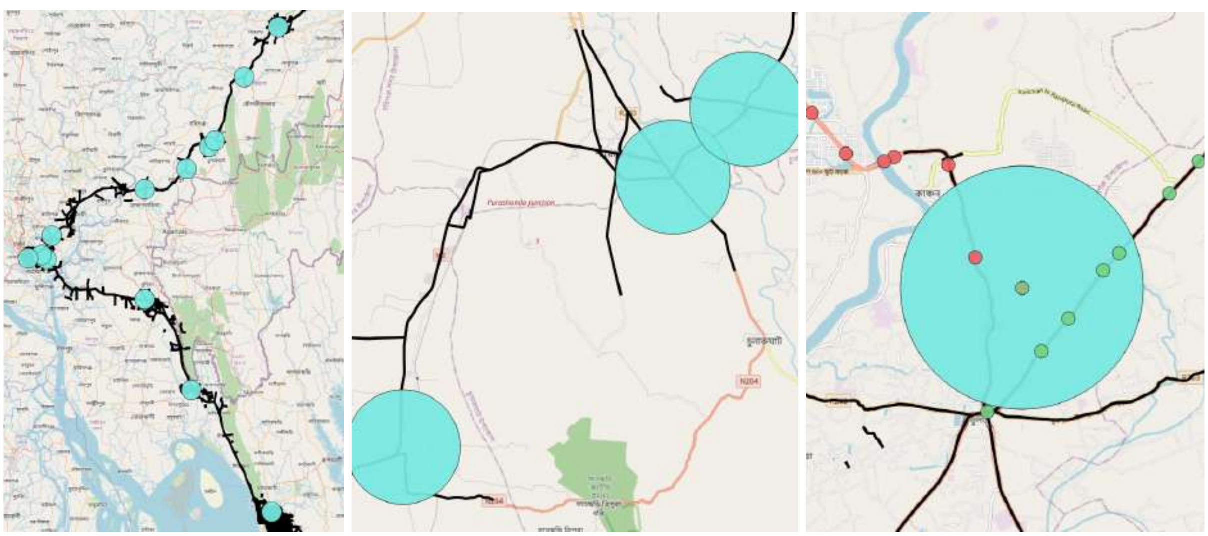

Figure 2: (Left) Zoomed-out depiction of points; (Centre) Accurate position of intersections; (Right) Inaccurate position of intersections where red is N105 and green is N2

Our observations show that for all 13 intersections identified, all 13 were true. However, the spatial accuracy for the intersections varies - Figure 2 (Centre) shows examples of good alignment with ground truth. In contrast, Figure 2 (Right) shows some anomalous cases where intersections are outside the 3km tolerance radius. Upon further inspection, this concerns inaccuracies within the LRP positions. This becomes an issue in the network model through inaccurate node connections, and as a result, the vehicle takes a path that might need to be more representative of reality.

2.2 Model Structure and Implementation

The BangladeshMode is an agent-based model composed of different components. Since providing a clear overview of the components and their relationships in the text is challenging, a UML diagram is used instead (Figure 3).

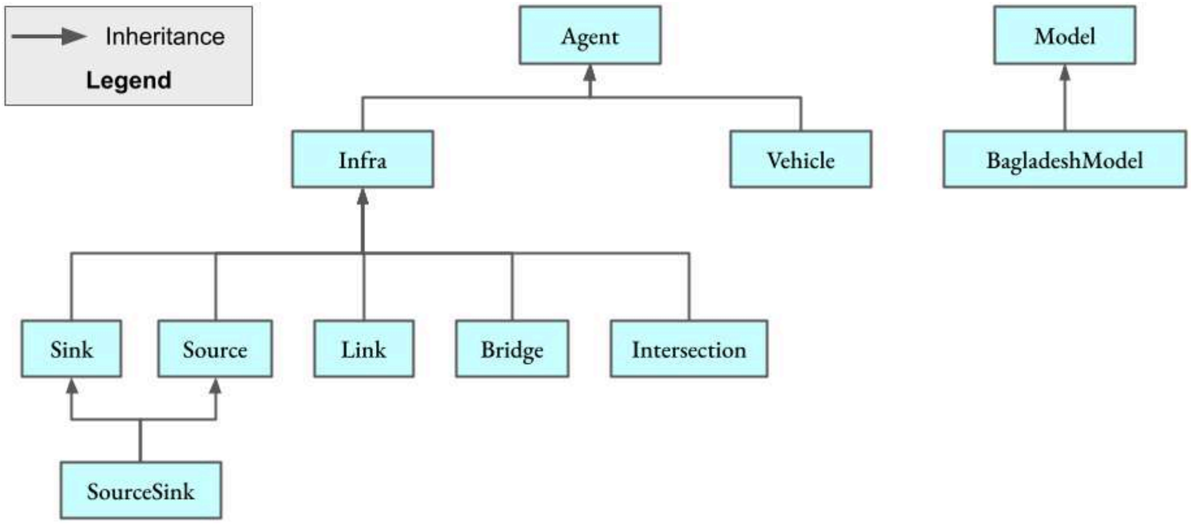

Figure 3. Simplified UML of the BangladeshModel that displays the different classes and subclasses. The arrows indicate the inheritance structure.

2.2.1 Modifications to BangladeshModel

The overall structure of the Bangladesh Model remains the same. However, to account for the various paths a truck can take within the expanded transport network, a dictionary called path_ids_dict is generated to store different routes' path IDs.

Furthermore, a new class called SourceSink (a subclass of both the Source and Sink classes) is used to handle the new behavior of trucks that can be created and removed at each start (source) and endpoint (sink). Additionally, the class Intersection has been introduced to address the increased complexity of the transportation infrastructure. It inherits the attributes of the Infra class.

2.2.2 NetworkX Generation

Node	Road	Model_type	Name	Length
1	N1	sourcesink	SoSi1	1
2	N1	link		1800
3	N1	intersection		20
4	N1	link		1400
5	N1	bridge		500
6	N1	link		200
7	N1	sourcesink	SoSi2	1
8	N2	link		1500
3	N2	intersection		20
9	N2	link		800

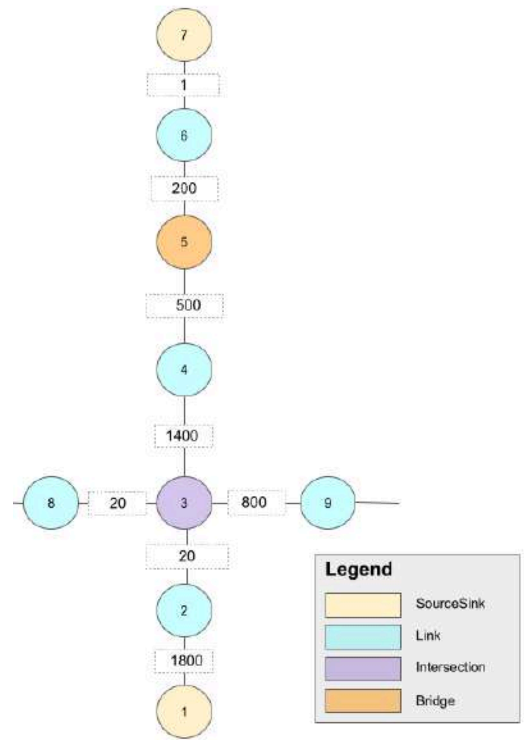

Figure 4. Conceptual Diagram of how the transport network of Bangladesh is implemented using python NetworkX library.

This network is generated by looping through all elements in *infrastructure.csv* in *generate_network()* and then passed to the model. Every transport infrastructure component (SourceSink, Link, Bridge, Intersection) is conceptualized as a node. The weights of the edges represent the length of the components by using the length of the next node in the order of the initial CSV file (compare Figure 4). Every time a new route needs to be searched, the model employs the network to locate the shortest path, utilizing the Dijkstra Search algorithm.

2.2.3 Multi-model Integration

We have adjusted the get_route method. Every time a truck is generated, it is assigned a random destination from the SourceSink class. To determine the exact path from source to sink, the model checks if the path already exists in the *path_ids_dict*. If the path exists, the truck follows it. However, if the path has not been explored, the model calls the *nx.shortest_path()* function to find the shortest path between the source and sink pair. To reduce computational time, the model stores all paths that have been traveled and their reverse paths in the *path_ids_dict*.

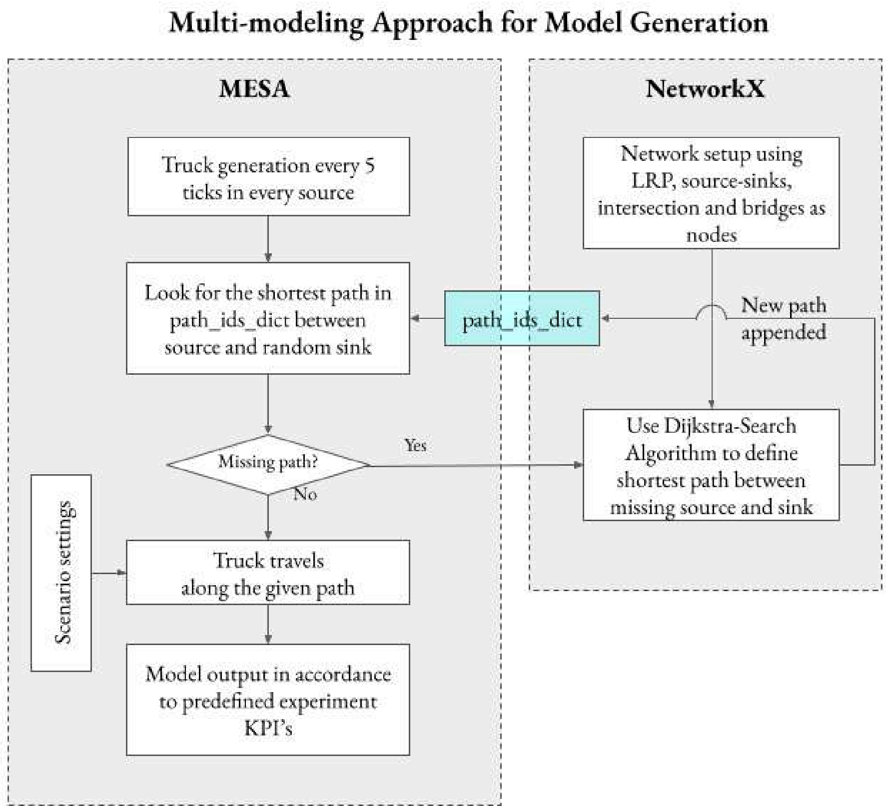

Figure 5. Flowchart of the Multi-model approach illustrating the interactive behavior between the Mesa BangladeshModel and the NetworkX model

2.3 Experiment Design and Setup

We use the BangladeshModel to analyze five different disaster scenarios and their associated effects on delay times of bridges. By examining multiple scenarios, we can increase the robustness of our resilience assessment and reduce uncertainty.

In each scenario, a truck is generated every 5 minutes at every SourceSink. The trucks travel at a speed of 48 km/h. The model runs in steps, with each step accounting for one minute. When the trucks encounter a damaged bridge, a delay time is calculated using the bridge length (Table 3) and the delay time probabilities for each scenario and bridge category (Table 4).

Table 3. Bridge Delay Time

Bridge length	Delay time for a truck
> 200 m	Triangular(1, 2, 4) hours
50 - 200 m	Uniform(45, 90) minutes
10 - 50 m	Uniform(15, 60) minutes
< 10 m	Uniform(10, 20) minutes

Table 4. Time delay probabilities concerning bridge condition category

	Category			
Scenario	**A**	**B**	**C**	**D**
S0	0	0	0	0
S1	0	0	0	0.05
S2	0	0	0.05	0.1
S3	0	0.05	0.1	0.2
S4	0.05	0.1	0.2	0.4

It is crucial to understand the significance of designed experiments while creating a simulation model. This awareness helps improve the efficacy of the high-dimensional design of experiments, as Sanchez and Wan (2012) mentioned. In our experiment, a partial, fractional factorial design was used to reduce the number of experiments needed to capture bridge criticality meaningfully. Instead of varying all input factors, only time delay probabilities of the 4 bridge categories are accounted for. Also, instead of testing all possible combinations and levels of delay time probabilities, scenarios in incremental undesirability on an ordinal scale varied with the range of 0 to 0.4 in intervals of factor 2.

To assess bridge criticality in more detail, we identified three bridge characteristics.

Table 5. Level of Bridge Criticality

Bridge Characteristics	Qualiative Description
A) The position in the transport network.	Bridges with a high betweenness centrality are critical for the infrastructure network as many trucks have to pass this bridge to follow their shortest paths. If a bridge with a high betweenness centrality breaks down, the chance that many trucks are delayed increases.
B) The length of the bridge.	Bridges with higher lengths cause greater delay times and, thus, have a bigger impact on the overall transport functionality that influences the travel time within the network.
C) The condition of the Bridge.	The condition of a bridge determines the likelihood of unavailability. Bridges in bad condition are more likely to break down and, therefore, greatly impact the overall travel time.

3. Result analysis

3.1 Average Effective Speed (AES)

The base scenario 0 has, as expected, an AES of 48 since no bridge is damaged; hence no truck is delayed. All other scenarios have lower AES because of the bridge unavailability, which causes delays. The AES decreases to less than 20 km/h in Scenario 4, showing the impact of bridges on travel time.

Table 5. Table of Average Effective Speed per Scenario

Scenario	Average Effective Speed [km/h]
0	48.00
1	46.95
2	39.25
3	31.17
4	19.62

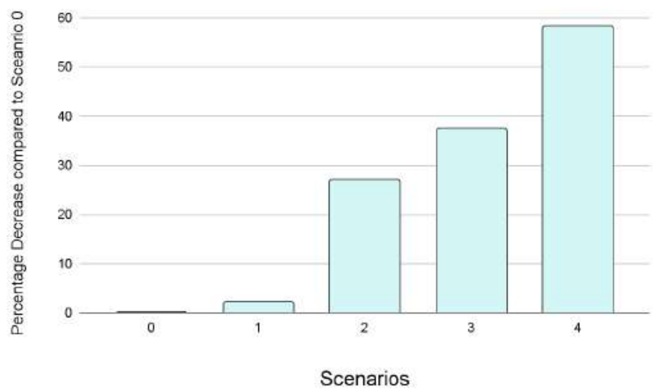

Figure 6. Percentage decrease in AES compared to the base scenario 0 speed of 48 km/h

We see that the percentage decrease in AES is the highest between Scenario 1 and 2. This shows the tremendous impact of condition C bridges' 5% breakdown probability. Especially long bridges, like the Kanchpur Girder Bridge, fall into that category and can cause up to 4 hours of delay. Hence, we see the relationship between travel time and bridges on the route.

3.2 Total Delay Time (TDT)

For each scenario, we calculated the total delay time that each bridge caused in the simulation. The results shown in Figure 6 present a heavy-tailed distribution where the average values are highly skewed towards 0 by the large number of bridges that do not present any delay due to how the scenarios are defined. On the other hand, these results show that the outliers of each scenario increase progressively with each scenario. As the ultimate objective of the study is to prioritize investments in bridges further assessing these outliers is highly relevant.

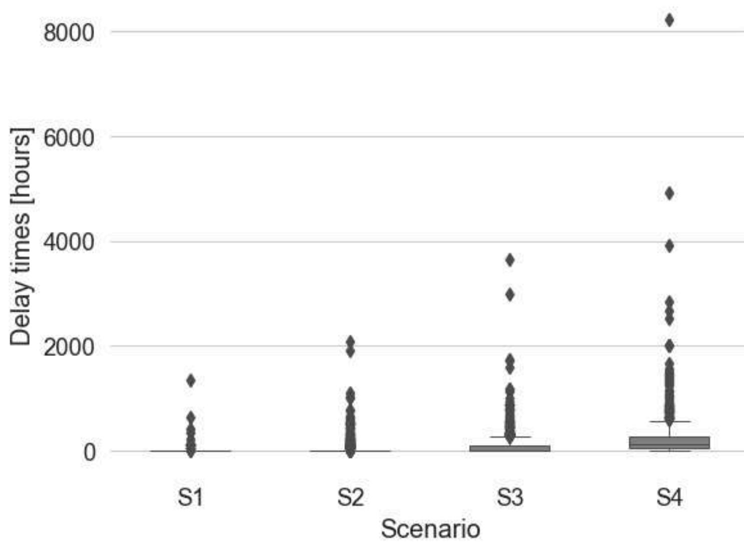

Figure 6. Boxplot of total delay times per scenario over the whole simulation. The outliers highlights the importance of exploring these bridges in our assessment of criticality

To further identify the most critical bridges, we computed which bridges are included in the top 10 bridges with the highest TDT for each scenario (Appendix C). The bridges that appear in the top 10 of more scenarios can be considered as the ones that can have a more significant impact on the travel time of the network under a wide array of possible disturbances.

We have identified 3 bridges that are among the top 10 that generate the highest delays in every scenario. These three bridges are all condition “D” bridges with a length higher than 50 m. The other “D” bridges on this list are only among the top 10 in two or less scenarios because they are less than 50m long or they present a normalized vehicle count below 49.

The rest of the bridges in this list are of condition C. The ones that are among the top 10 in 3 scenarios present have more than 50 m and a very high normalized vehicle count which means they are among the ones with the highest betweenness centrality in the network.

4. Discussion and Limitations

Main Findings

We discovered that the condition of the bridge is the most significant characteristic affecting overall transportation connectivity. This was evident in all four scenarios modeling bridge unavailability, where all critical bridges were rated as condition D or C. Normalized vehicle count seems to play some part in the criticality of the bridges. As normalized vehicle count is largely dependent on the spatial structure of the network, it hints at our future work to look into network metrics such as betweenness centrality. Finally, we observed that the top 5 bridges are largely >200m - however, not all >200m bridges have great delay time. Hence, bridge length as a characteristic does not seem like a necessary condition for bridge criticality.

Limitations of Models

There are assumptions in the way we model vehicular movement. We set a constant speed and did not model vehicle-to-vehicle interaction (congestion). The bridges were also simplified, where we combined the parts of the bridge (left and right) into one appropriate for the aggregation and scoping of the model. There is also no real-world data to test the assumption of bridge damage percentage. The current model also does not include a risk assessment of road maintenance.

Limitations of Assessments and KPIs

The TDT and AES were used to assess the delays in the network. Both are related to criticality metrics that can be categorized as *utilitarian* metrics (Jafino et al., 2020). As utilitarian metrics are not used, the assessment can be criticized because fairness and equity are disregarded. Furthermore, travel cost and connectivity are ignored, as our metrics only assess the accessibility of the network.

Inaccuracies and Uncertainties

In our network generation, we defined edge weights based on the length recorded in the succeeding node - this is to standardize and simplify the generation process. However, this creates a bias towards a certain direction of travel in the network and a source of inaccuracies in the lengths of routes. Also the positional errors on the infrastructure data influenced the intersection connections in the network - leading to suboptimal shortest-path routes. This highlights spillover effects from errors in our previous dataset that must be acknowledged and managed.

Future Extensions

In our design of the experiment, we focused much more on output measures to understand ways to quantitatively analyze bridge criticality. In future experiments as the policy questions get more specific, there can be more ways to test input variables, both controllable and uncontrollable to understand a greater range of influences on bridge criticality (Sanchez and Wan, 2012).

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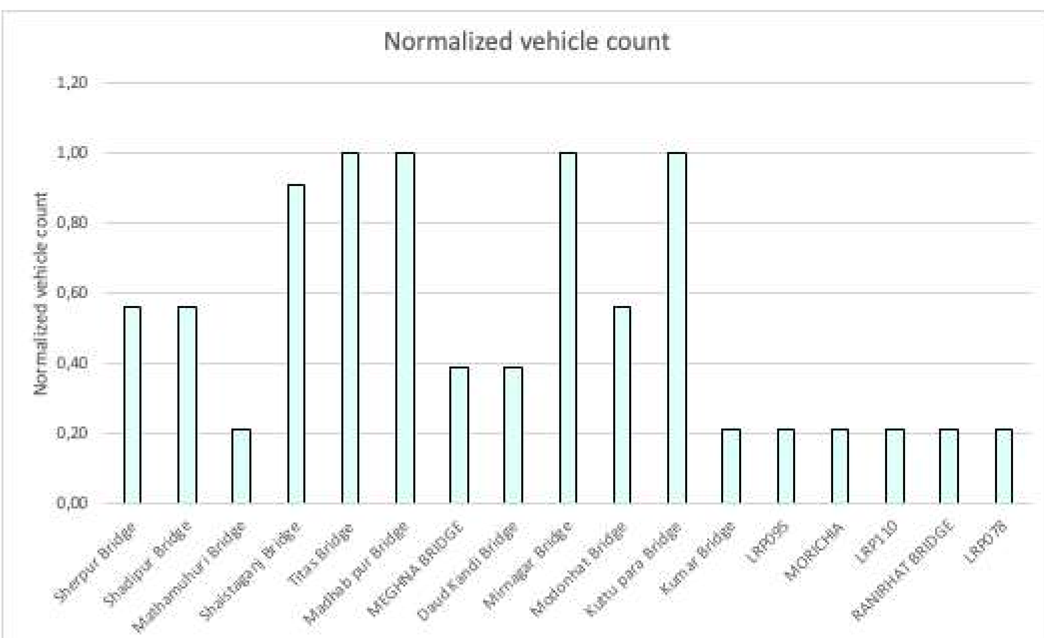
Appendix A

Table A1: Quantity of Bridges as per bridge length and condition

		Length				
		<10 m	**10-50 m**	**50 - 200 m**	**>200 m**	**Total**
Condition	**A**	425	188	18	4	**635**
	B	92	74	19	2	**187**
	C	60	91	19	6	**176**
	D	8	14	2	2	**26**
	Total	**585**	**367**	**58**	**14**	**1024**

Appendix B

Figure A1: Normalized vehicle count per top-10 bridge



Appendix C

Table A2: Bridge describing its occurrences in top 10 average delay time across scenarios and its characteristics

	Appearance in top 10 total delay time					Bridge characteristics		
Bridge name	**S1**	**S2**	**S3**	**S4**	**Total**	**Length**	**Condition**	**Normalized vehicle count**
Sherpur Bridge	1	1	1	1	**4**	>200 m	D	0.56
Shadipur Bridge	1	1	1	1	**4**	50 - 200 m	D	0.56
Mathamuhuri Bridge	1	1	1	1	**4**	>200 m	D	0.21
Shaistaganj Bridge	0	1	1	1	**3**	>200 m	C	0.91
Titas Bridge	0	1	1	1	**3**	50 - 200 m	C	1
Madhab pur Bridge	0	1	1	1	**3**	50 - 200 m	C	1
MEGHNA BRIDGE	0	1	1	1	**3**	>200 m	C	0.39
Daud Kandi Bridge	0	1	1	1	**3**	>200 m	C	0.39
Mirnagar Bridge	0	1	1	1	**3**	10-50 m	C	1
Modonhat Bridge	1	0	0	1	**2**	10-50 m	D	0.49
Kuttu para Bridge	0	1	1	0	**2**	10-50 m	C	1
Kumar Bridge	1	0	0	0	**1**	50 - 200 m	D	0.21
LRP095	1	0	0	0	**1**	10-50 m	D	0.21
MORICHIA	1	0	0	0	**1**	10-50 m	D	0.21
LRP110	1	0	0	0	**1**	10-50 m	D	0.21
RANIRHAT BRIDGE	1	0	0	0	**1**	10-50 m	D	0.21

Report Assignment 4

Bangladesh Transport Network

A Geospatial Data Analysis Approach

EPA1352: Advanced Simulation

7. April, 2023

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

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Words: 4974

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.

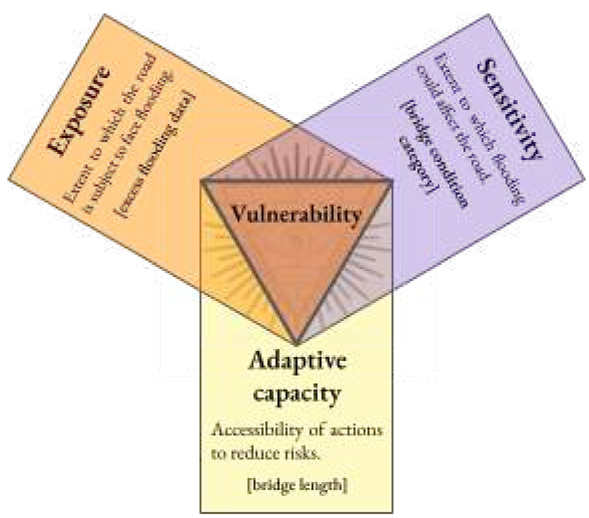

Figure 2. Indicators of Vulnerability: Exposure, Sensitivity and Adaptive Capacity (Rowan et al., 2014)

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.

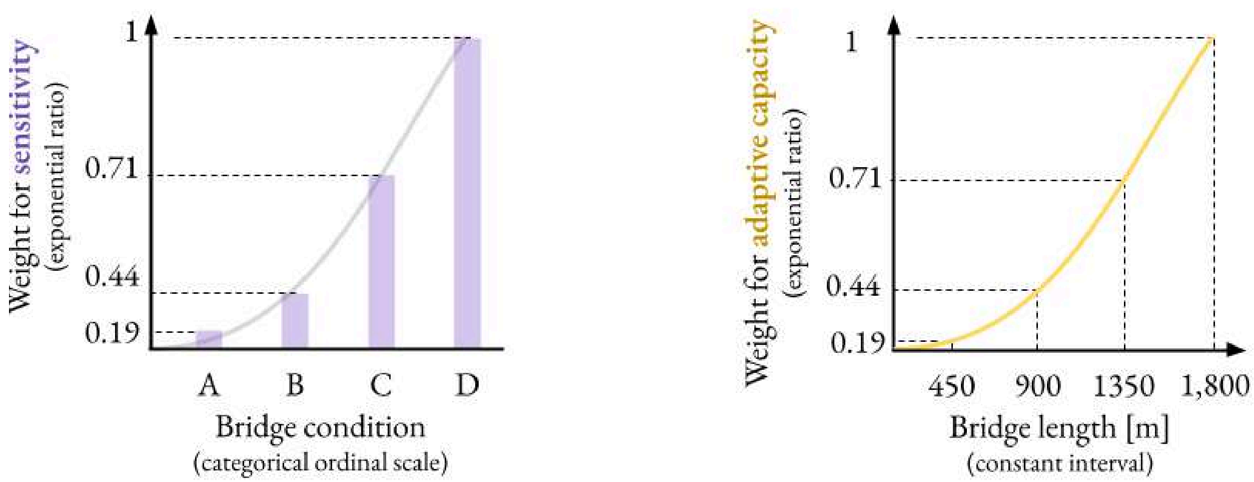

Figure 3. Illustration of Weight Estimation for the Weighted Sum Equations of Vulnerability Indicators Using an Exponential Relation with a 1.2 Progression Factor

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 was 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.

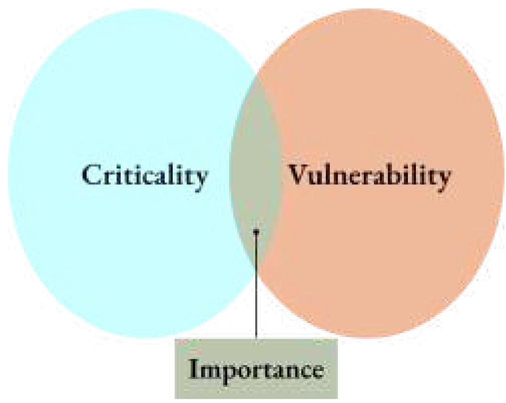

Figure 4. Venn Diagram to Illustrate the Relationship Between Vulnerability, Criticality and Importance

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

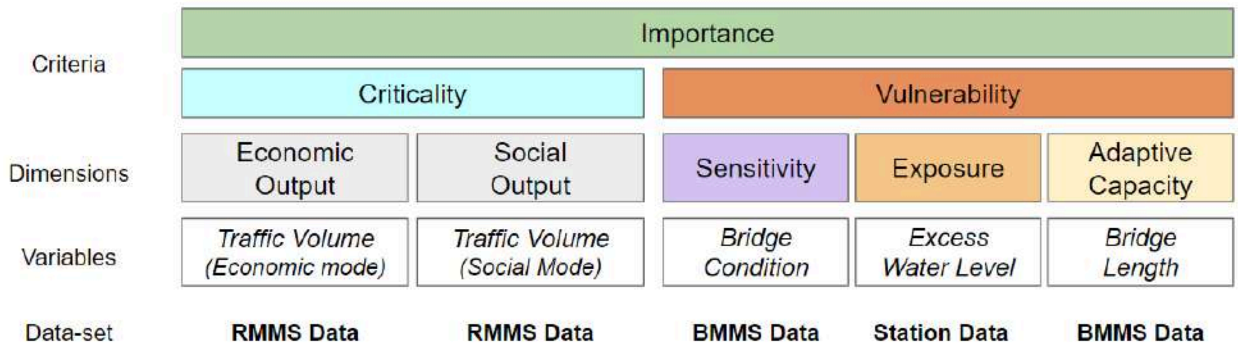

Figure 5. Overview of Criterias, Variables and Data Source

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

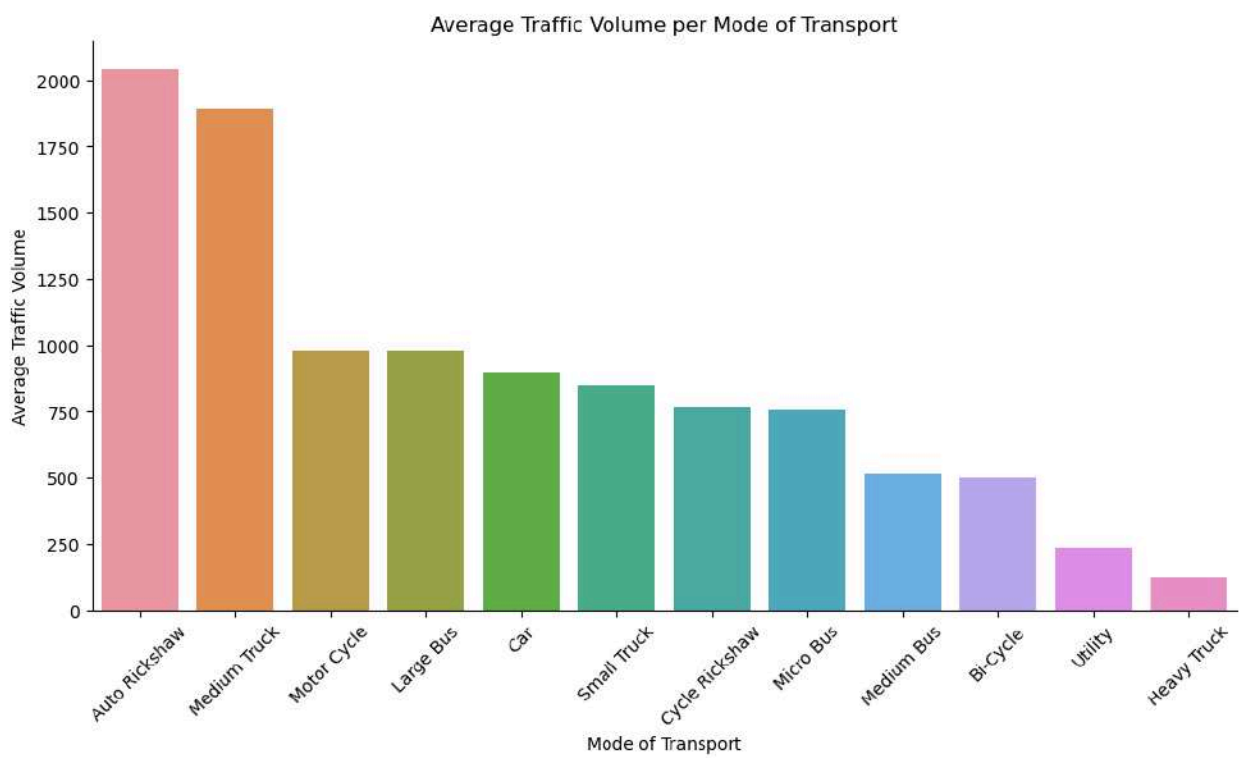

Figure 6. Bar Graph of Average Traffic Volume per Mode of Transport

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

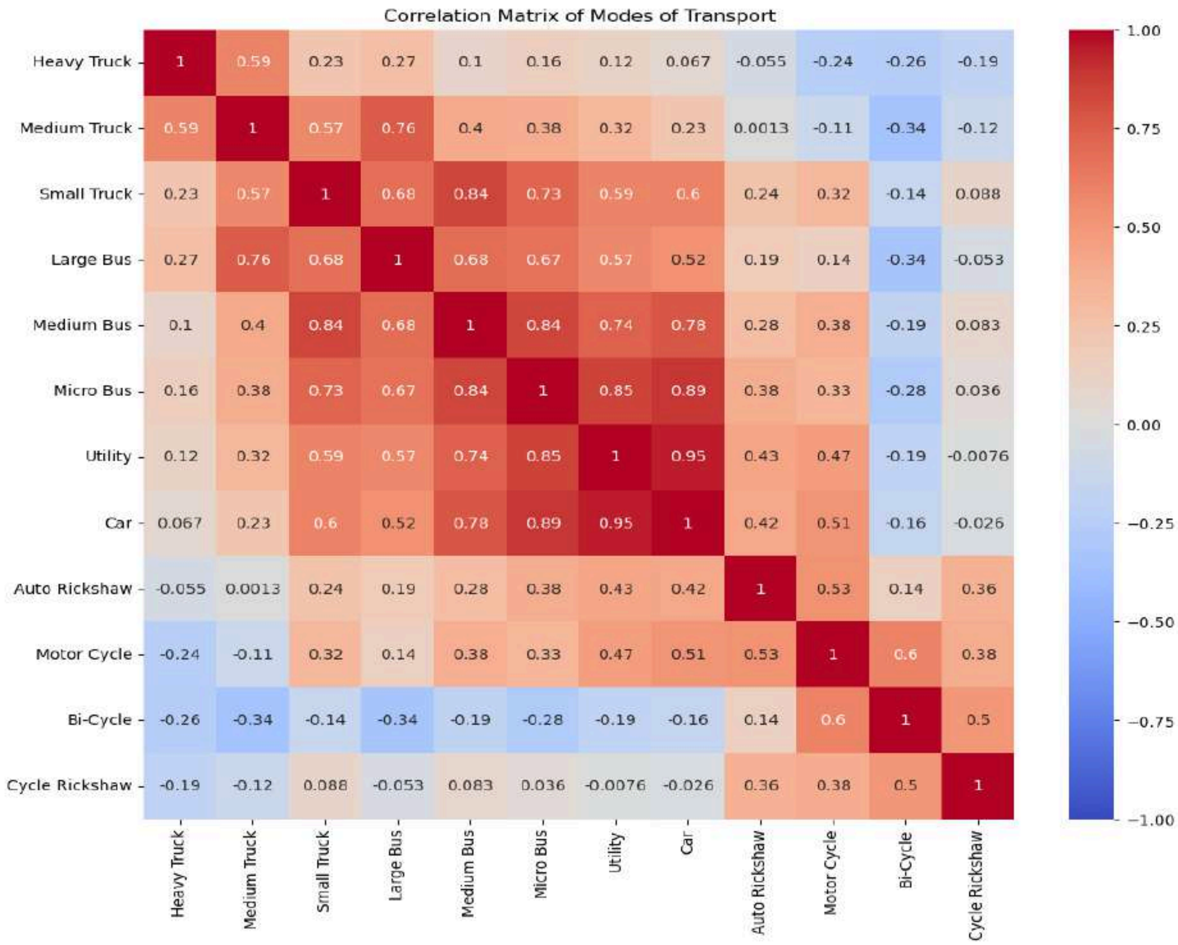

Figure 7. Heatmap of Correlations Between Traffic Volumes of Different Transport Modes

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

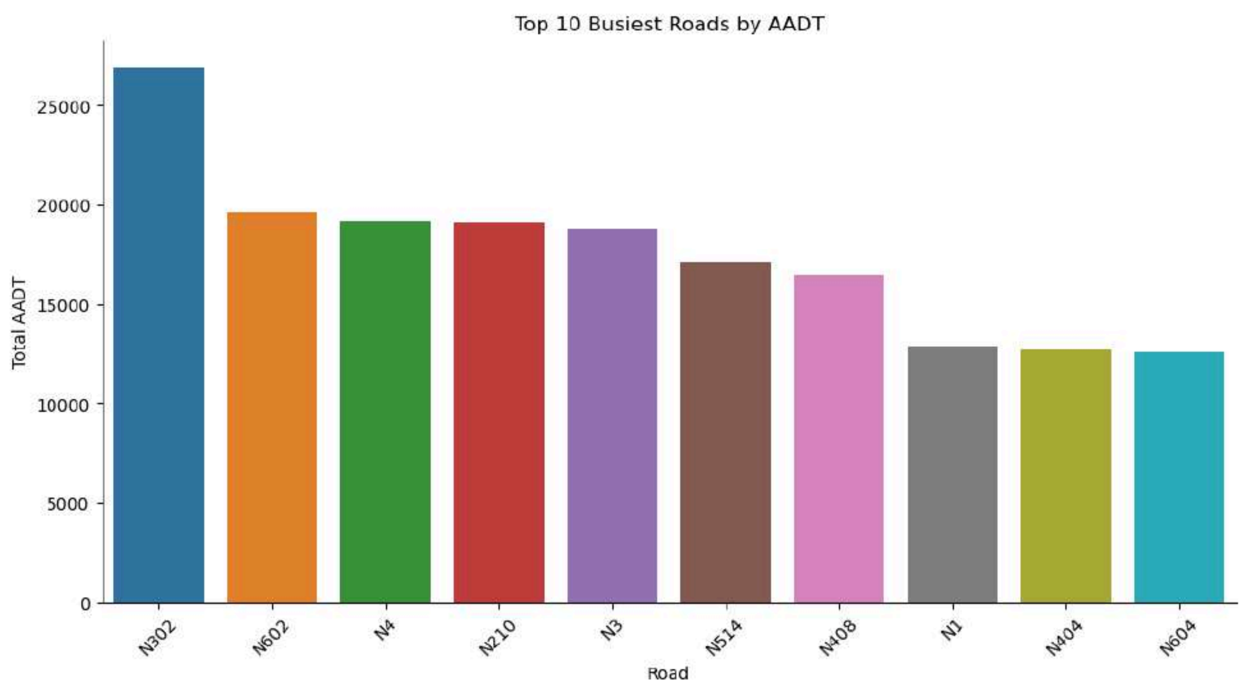

Figure 8. Bar Graph of Busiest Roads by Annual Average Daily Traffic

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.

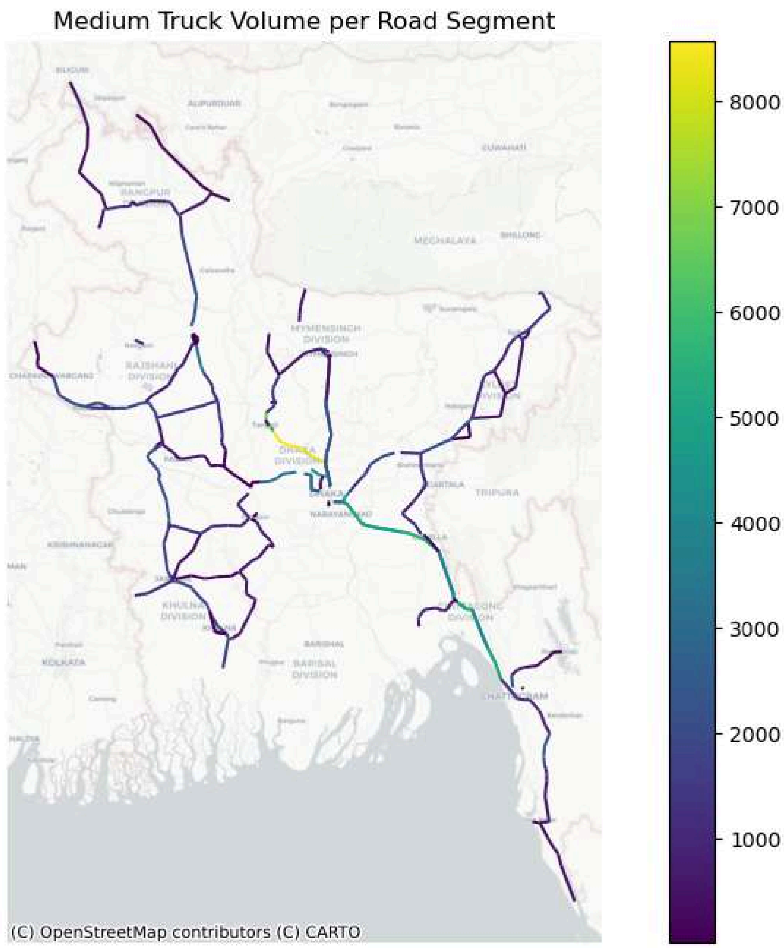

Figure 9. Map of Road Network coloured based on Traffic Volume of Medium Trucks

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.

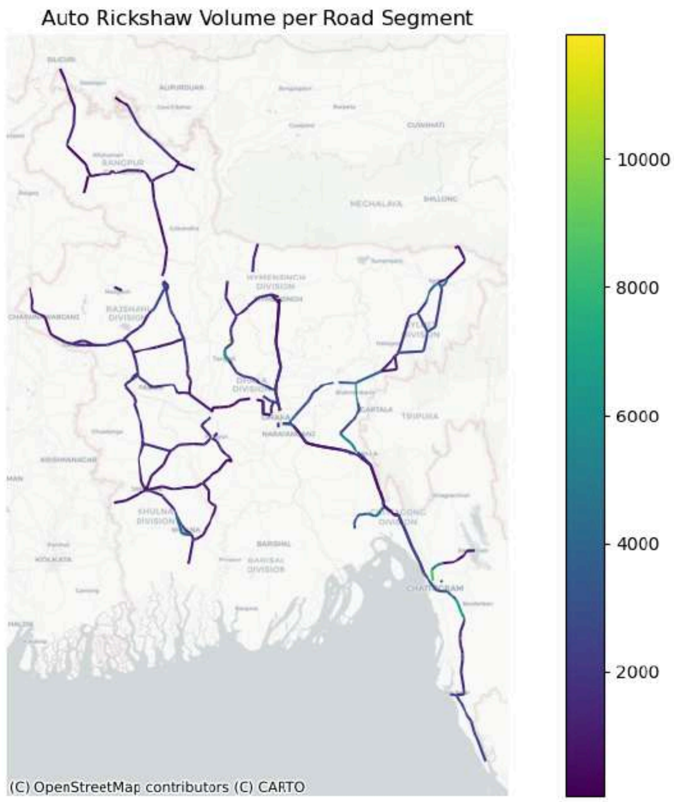

Figure 10. Map of Road Network Coloured Based on Traffic Volume of Auto Rickshaw

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

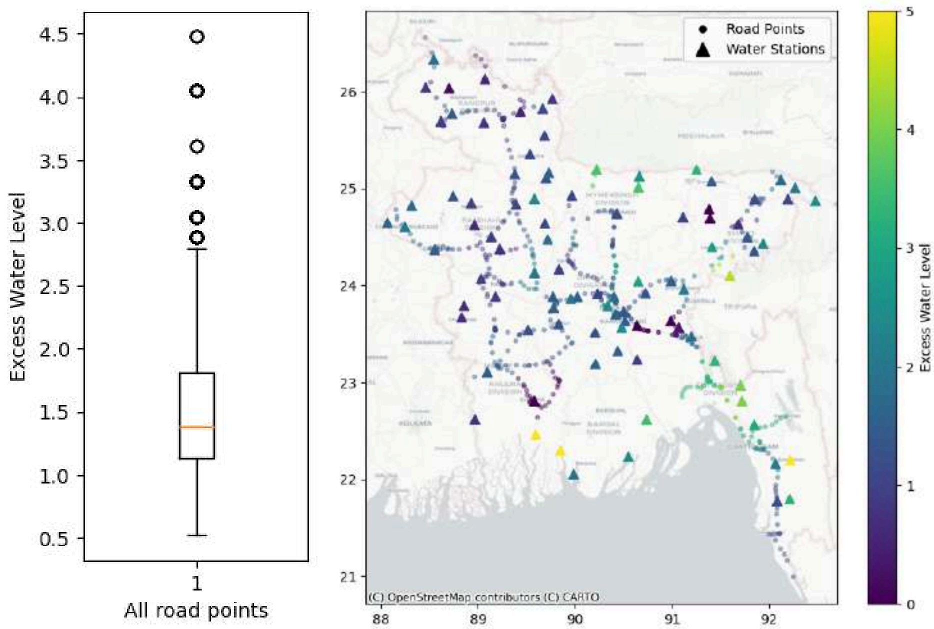

Figure 11. Graphs of Excess Water Level; Numerical Distribution (Left) Spatial Distribution (Right)

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

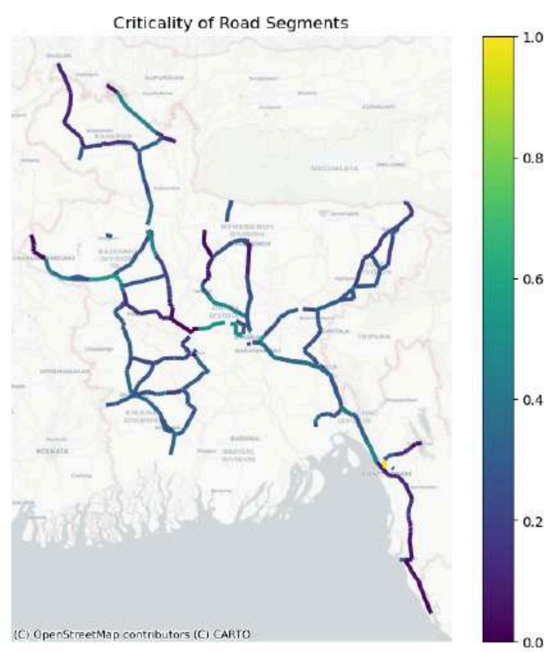

Figure 12: Map of Criticality Index for Road Segments

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

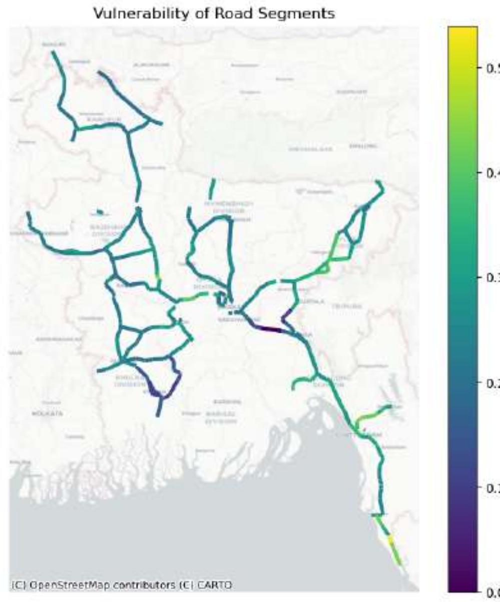

Figure 13: Map of Vulnerability Index

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

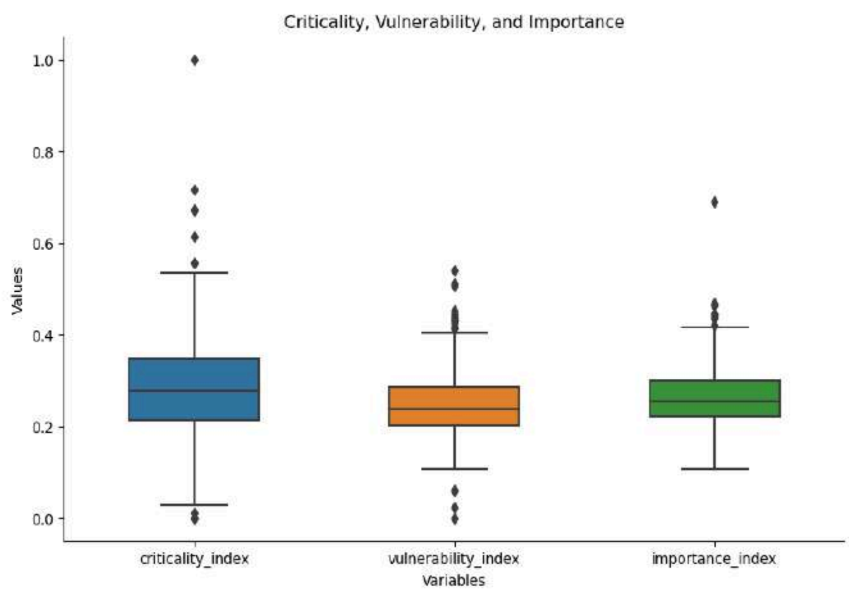

Figure 14. Box Plot Illustrating the Range of Criticality, Vulnerability and Importance

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.

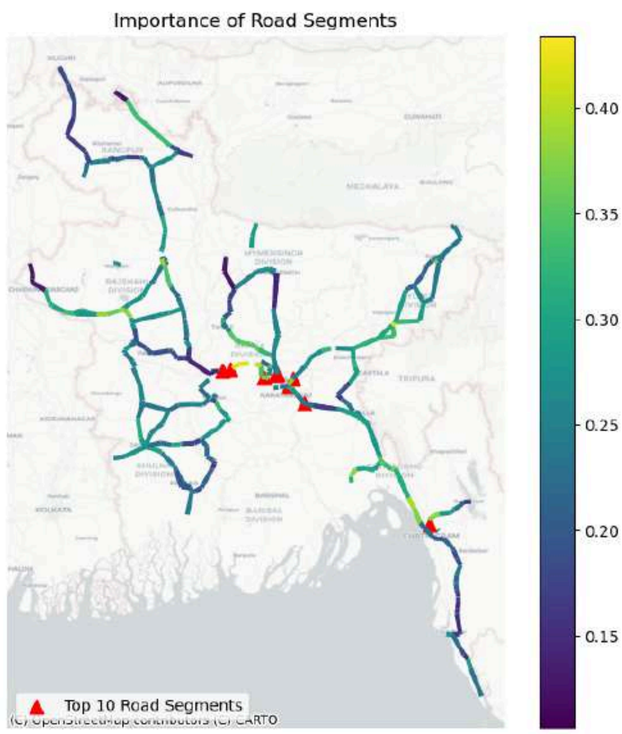

Figure 15: Map of Road Network with the Top 10 most Important Road Segments represented by Red Triangles

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)

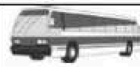
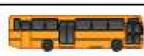
No	Picture	RHD Category	Description and Representative Models
a) Motorised Vehicle			
1.		Heavy Truck	Trucks with three or more axle which includes multi-axle tandem trucks, container carriers and articulated trucks. **Model: Tata LPT 2516**
2.		Medium Truck	Trucks with two axles and carries over three 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.