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Faculty of Technology, Policy and Management

Delft University of Technology

EPA1351 - Advanced Discrete Simulation

DATA VISUALIZATION - VULNERABILITY AND CRITICALITY OF INFRASTRUCTURE IN BANGLADESH

- Lab Assignment 3 -

Group 3

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Introduction

The purpose of this assignment is to identify the potential impacts of natural disasters on the road network in Bangladesh. Bangladesh experiences three main types of natural disasters: earthquakes, riverine flooding and hurricanes (Gray & Mueller, 2012). During these natural disasters there can be significant damage to the country's infrastructure network, which has implications for the delivery of relief goods, and the ability of agencies to provide aid and support to those in need.

As part of a World Bank project for potential infrastructure upgrades, this analysis will define and visualize the most critical and vulnerable sections road infrastructure within the country. To determine which areas require the most funding, the World Bank needs to know which elements of the infrastructure are highly susceptible to damage and the potential level of damage caused by a loss of these elements (i.e vulnerability), as well as which elements are the most important to maintain under normal and potentially extreme circumstances (i.e. criticality).

This report contains the three sections to reach the best possible identification. First, the concepts of vulnerability and criticality are more fully defined based on literature. Second, interactive visualizations are created to inspect the roads according to the previously defined concepts. And finally, the 10 most critical and 10 most vulnerable roads are identified.

Chapter 1

Criticality and vulnerability

The first step in identifying the most vulnerable and critical roads in Bangladesh is by creating clear definitions. Based on a detailed literature review, the existing definitions of vulnerability and criticality will be discussed, and used to develop a specific framework for this exercise. This framework will then be used in chapter 3 to identify the most important roads for the government of Bangladesh.

1.1 Definitions in literature

1.1.1 Vulnerability

There are multiple definitions of vulnerability in literature. Birkmann notes up to 25 definitions, concepts and methods to systematize vulnerability (Birkmann, 2006). One of the simpler definitions is from Cordona and defines vulnerability as an *"intrinsic predisposition to being affected by or susceptible to damage"*. (Cordona, 2004, as cited in (Birkmann, 2006)). An extended and synthesized version of this definition by Birkmann states that*"vulnerability represents the system or community's physical, social or political susceptibility to damage as a result of a hazardous event of natural or anthropogenic origins*(Cardona, 2004; 37-51; as cited in (Birkmann, 2006)).This extended version highlights the different kinds of vulnerability, as well as the different causes (i.e. natural or human).

Another definition of vulnerability emphasizes the multi-dimensional, scale-dependent and dynamic nature of vulnerability (Vogel and O'Brien, 2004:4; as cited in (Birkmann, 2006)).

Vulnerability is also associated with the idea of risk, which is defined in the natural hazard and epidemiological fields (Downing et al., 2005) as

Risk = Hazard x Vulnerability

where *Hazard* is the potential threat to humans and their welfare; *Vulnerability* is the exposure and susceptibility to losses;*Risk* is the probability of a hazard occurring; and, *Disaster* is the realization of risk (Downing et al., 2005). This definition focuses on how vulnerability is linked to exposure to events, as well as the susceptibility to losses or damage from said event.

A more technical definition is given by Kaperson et al. as *"the degree to which an exposure unit is susceptible to harm due to exposure, to a perturbation, or stress, in conjunction with its ability (or lack thereof) to cope, recover, or fundamentally adapt."* (Kaperson et al, 2000, as cited in (Downing et al., 2005)). And similarly, the UNDHA defines vulnerability as the degree of loss (from 0 to 100%) resulting from a potential damaging phenomenon (UNDHA, 2003; as cited in (Downing et al., 2005)).

What all these definitions have in common is that vulnerability involves the susceptibility to loss and damage caused by external (natural or human) events. Using these concepts as the basis of a working definition for vulnerability; we decided to develop a vulnerability index for defining road network vulnerability in this exercise, which is further explored in **Section 1.2**.

1.1.2 Criticality

In a 2017 paper by Kim and Yeo, criticality is defined at a high level as being synonymous with "importance", and represents only the consequence of a disruptive event, regardless of the probability of such an event occurring (Kim & Yeo, 2017). Consequently, according to this definition, *the more critical (i.e. important) an element is, the larger the damage that is caused when the element malfunctions* (Kim & Yeo, 2017).

Another definition of criticality is taken from a 2018 paper analyzing the Spanish high capacity road network criticality (García-Palomares, Gutiérrez, Martín, & Moya-Gómez, 2018). This paper highlights a clear link between road network criticality and

vulnerability with the definition, *"The critical elements of a network (links or nodes) are those that most affect its vulnerability: the more critical the element, the greater the effects of its loss on the system."*(Taylor et al. (2006), Jenelius et al. (2006), as cited by (García-Palomares et al., 2018) The paper also highlights a definition of vulnerability by Jenelius and Mattson, as based on the potential degradation of the road transport system (Jenelius and Mattson, 2015, as cited in (García-Palomares et al., 2018)).

Definitions of criticality specific to this exercise are centered around economic importance, represented by the number of trucks per road. However, traffic density and congestion factors, such as the Average Annual Daily Traffic (AADT) per road segment are indicative of the total volume of traffic in a road segment. Congestion on a roadway can be determined with the AADT and number of lanes per segment and is indicative of how busy a road is; but is not included in this assessment.

The above definitions consider criticality in terms of importance to the continued functioning of a system; and note that criticality is intrinsically linked to vulnerability. Using these definitions as a basis of understanding the concept, a criticality index for classifying road network criticality was developed and is discussed further in **Section 1.3**.

1.2 Vulnerability Index (VI)

The vulnerability index (VI) was developed to classify full roads and road segments in the Bangladesh road network. It is based on the definitions of vulnerability found in the literature and uses key variables in the available data to identify these vulnerabilities. The following section outlines the variables and assumptions used in the index.

1.2.1 Variables of Vulnerability

Two variables are utilized to determine vulnerability, both relating to the amount of bridges on a road. The bridges are analysed based on their condition. For every road and segment the bridges are counted. For every bridge the road/ segment receives one vulnerability point. The bridges of quality A receive 1 point, bridges of condition B 2 points, condition C 3 points and finally condition D 4 points. The sum of all point defines how vulnerable a specific road or segment is. The results will be normalized to achieve the Vulnerability Index. Both variables used in the analysis are shown in the following list:

- Number of bridges on the road (#)
- Structural conditions of the bridges (A = 1 point, B = 2 points, C = 3 points, D = 4 points)

1.2.2 Assumptions

During the analysis of the roads with the use of the points per bridge four assumptions have been made, which are as follows:

- Longer roads are more vulnerable (i.e. more potential for breakdowns in different or multiple segments of the road)
- Roads with more bridges are more vulnerable (i.e. more potential for disruptions to traffic should bridges break down)
- Roads with longer bridges are more vulnerable (i.e. longer bridges have longer repair/maintenance times, leading to longer delays in travel time should they breakdown)
- Roads with bridges with structural condition D are more vulnerable (i.e. roads with a poor structural condition are more susceptible to breakdowns due to significant external stresses).

1.3 Criticality Index (CI)

The criticality of a road segment is determined by the importance of that segment. The importance is in this case determined by the economic importance, based on the amount of goods transportation. It suggests that the more goods transport on a road segment, the higher the criticality of the road. The total amount of goods transported on each road will be calculated based on the weighted average of the carrying weight of different truck types on every road segment, as extracted from the data.

The weighted average carrying weight is based on the amount of goods every truck can carry in kilogrammes and the number of each type of truck present in the road segment. The data for the three different carrying weight classes - small, medium and heavy - are provided by the US Department of Energy (SOURCE: https://afdc.energy.gov/data/10380):

Table 1.1: Weight by truck type

Truck type	Carrying weight	Average weight	Average weight normalised
Small	0 to 4500 kg	2250 kg	0.10
Medium	4501 - 12000 kg	8250 kg	0.34
Heavy	12001 - 15000 kg	13500 kg	0.56

The average carrying weight of each truck-type differs. These averages are normalised and their normalisation is used in the equation for Criticality Index (CI):

$$CI = 0.10 * small\_truck + 0.34 * medium\_truck + 0.56 * heavy\_truck$$

In this equation, *small_truck* represents the number of small trucks per segment, and the same counts for *medium_truck* and *heavy_truck*.

1.3.1 Variables of Criticality

The variables that will be used for determining the criticality of a road segment are:

- Relative economic importance, defined as:
  *0.10 * small_truck*
  *0.34 * medium_truck*
  *0.56 * heavy_truck*

1.3.2 Assumptions

- Criticality of a road segment is only based on the economic importance.
- Economic importance is defined as cargo transportation possibility by different truck types: small, medium and heavy.
- Importance of each truck-type is determined by the relative weight they can carry.

Chapter 2

Visualizing the Road System

2.1 Traffic Density

Bangladesh's road system experiences experiences considerable traffic throughout the year. Mapping this road activity (see fig. 2.1) shows that there exists great variability in traffic, some roads receiving a high amount of vehicles throughout the year, and others less.

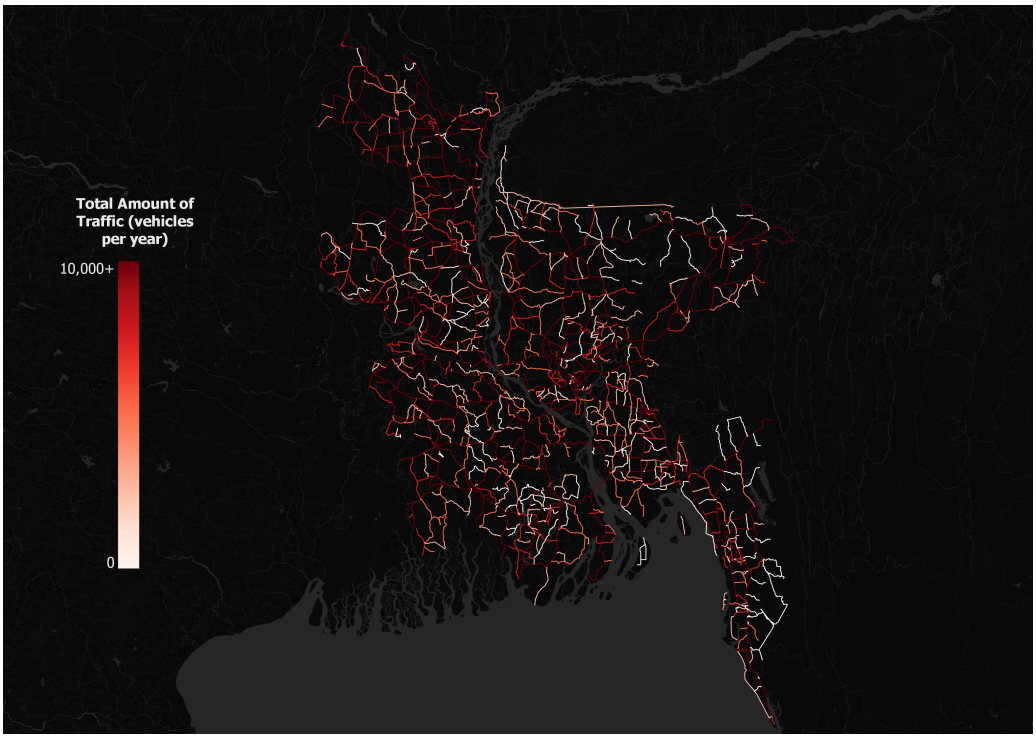

Figure 2.1: Yearly Traffic in Bangladesh's Road System

In this context, it is useful to explore how traffic density varies by mode of transport. A number of transport modes are used in Bangladesh, and by investigating which are more popular than others and where certain modes of transport occur most we can obtain more insight about criticality within the road system. Additionally, by identifying roads with more lower quality infrastructure, such as weak bridges, we can obtain insight about vulnerability within the road system.

(1) of fig. 2.2 shows a ridgeline plot of traffic density by Transport mode on all road segments. For each transport mode, the normalized distribution of traffic densities within each road segment is visualized. By visualizing normalized distributions as opposed to total traffic values or average traffic values, we not only are able to see which transport modes generate more road traffic on average, but we are also able to see whether some mode of transport generate variable levels of transport across road segments. For example, (1) of fig. 2.2 shows that while motorcycles or small trucks are generally responsible for higher levels of traffic on all road segments, heavy trucks contribute to a wider range of traffic levels across road segments. In other words, there are some road segments with very low traffic from heavy trucks and other road segments with very high traffic from heavy trucks.

In this context, truck traffic varies a lot across roads. (3) of fig. 2.2 shows the distribution of yearly truck traffic across the Bangladesh road system. (2) of fig. 2.2 highlights roads with a higher frequency of condition D bridges, which can be considered weak and impassable during flooding situations. By comparing (2) and (3) of fig. 2.2, we can see that many of such roads also have high amounts of truck traffic throughout the year.

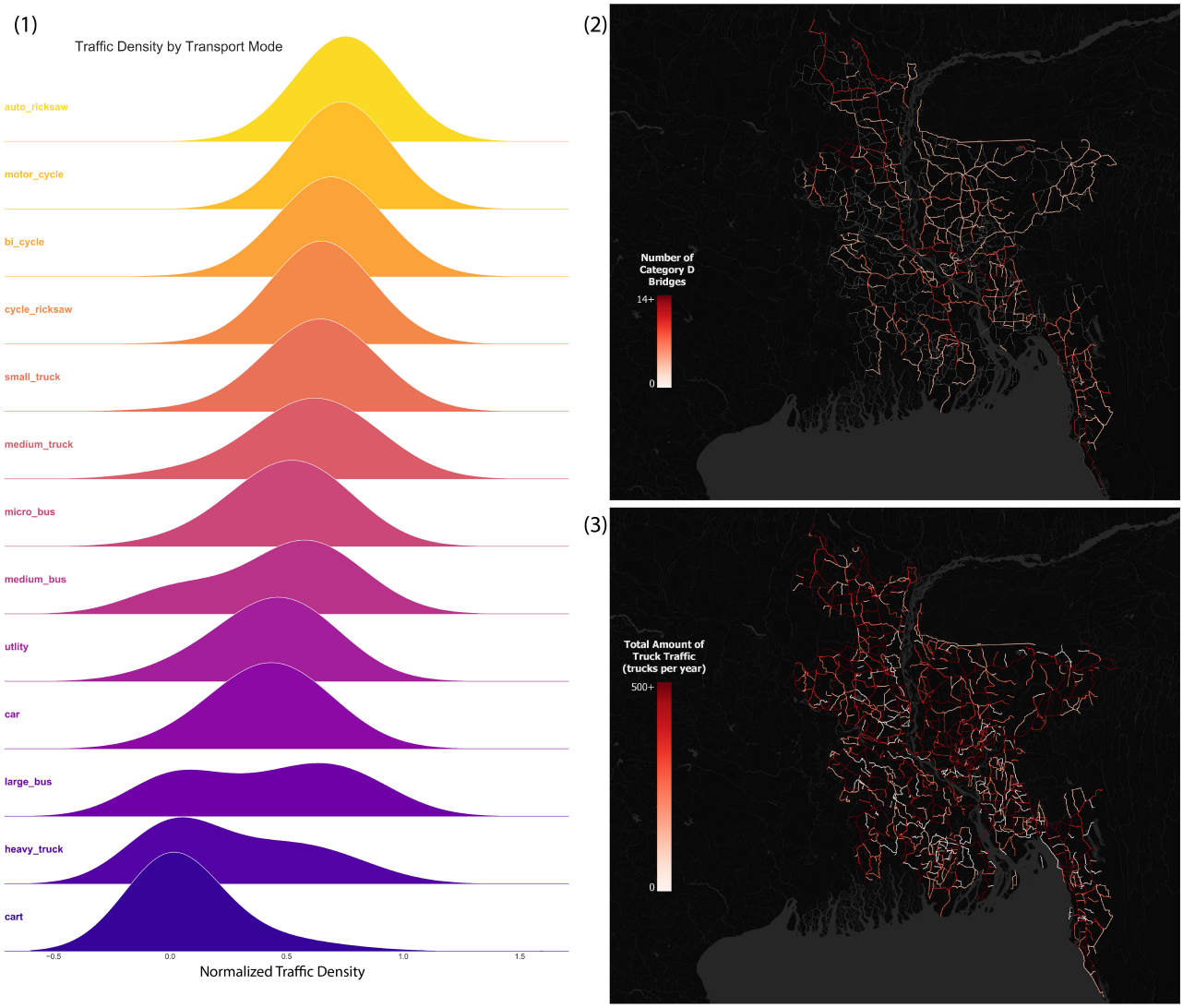

Figure 2.2: (1) Traffic Density by Transport Mode, (2) Category D Bridges in Bangladesh Road System, (3) Truck Traffic in Bangladesh Road System

2.2 Criticality and Vulnerability in the Road System

Computing and visualizing the Criticality Index (CI) and Vulnerability Index (VI) geographically reveals novel information about the Bangladesh road system. Figure 2.3 illustrates vulnerability (dark red being the most vulnerable roads) and criticality (the thickest lines being the most critical roads) for the Bangladesh road system. On one hand, this figure shows that the most vulnerable roads are not necessarily the most critical ones. In fact, many highly critical roads have mid-low levels of vulnerability. On the other hand, this figure shows that there are some roads that are both highly critical and highly vulnerable. These are the roads that should be focused on when investing in infrastructure, and planning disaster relief operations.

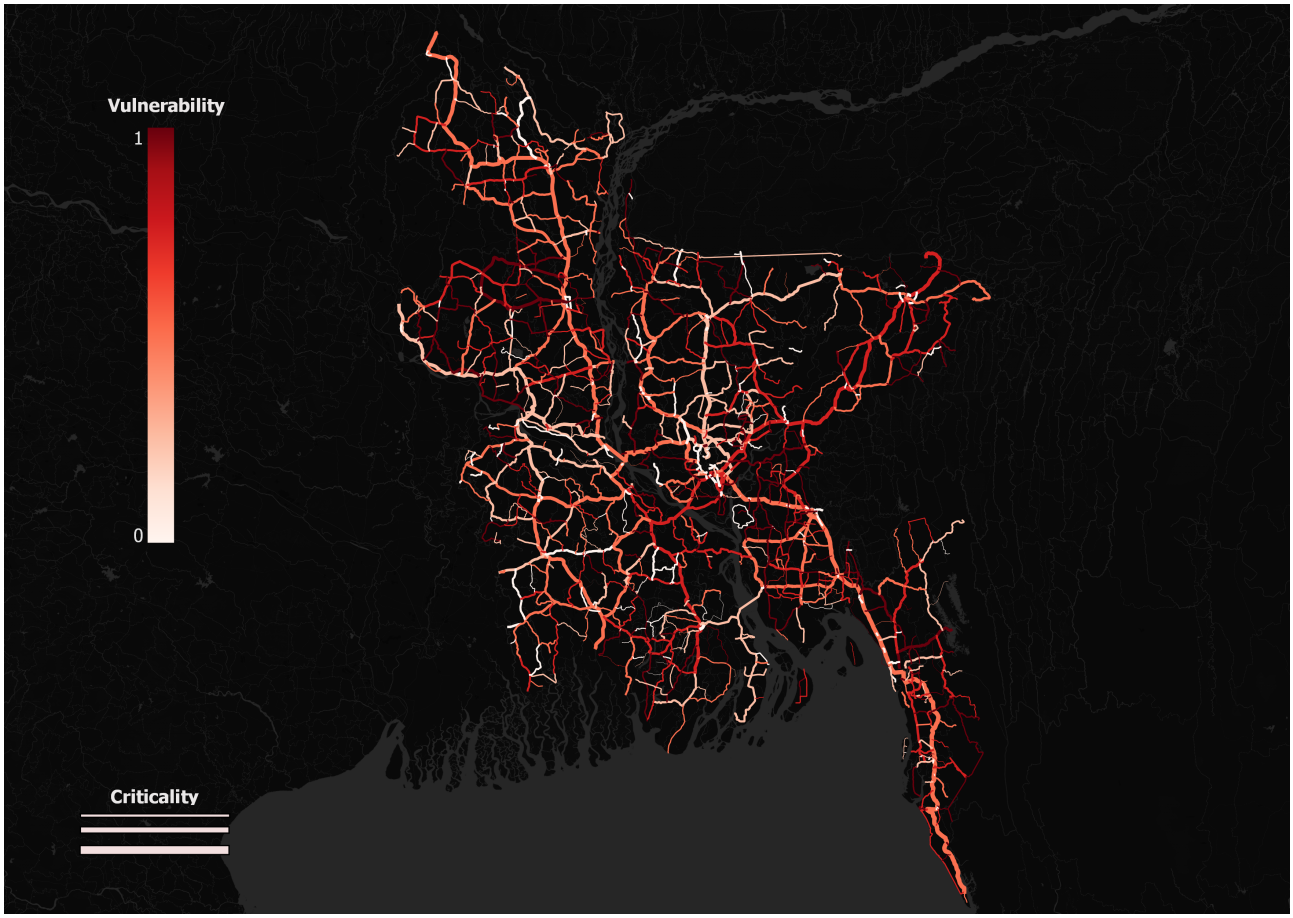

Figure 2.3: Criticality and Vulnerability of the Bangladesh Road System

Chapter 3

Most important roads

For the definition of the 10 most important roads, the criticality and vulnerability index will be used. First, both these indexes are determined for every road. Than a visualization will follow and the 10 most critical and vulnerable roads will be identified. Lastly, the longest road of Banladesh with the most segmenst (road N1) is analysed and visualised per segment.

3.1 Vulnerability/Criticality-index per road

The V/C-index for every road is based on the equations used in chapter 1. For every road, the criticality and the vulnerability is calculated, these can be seen in fig. 3.1. It shows that most roads have a high vulnerability or a high criticality, not both at the same time.

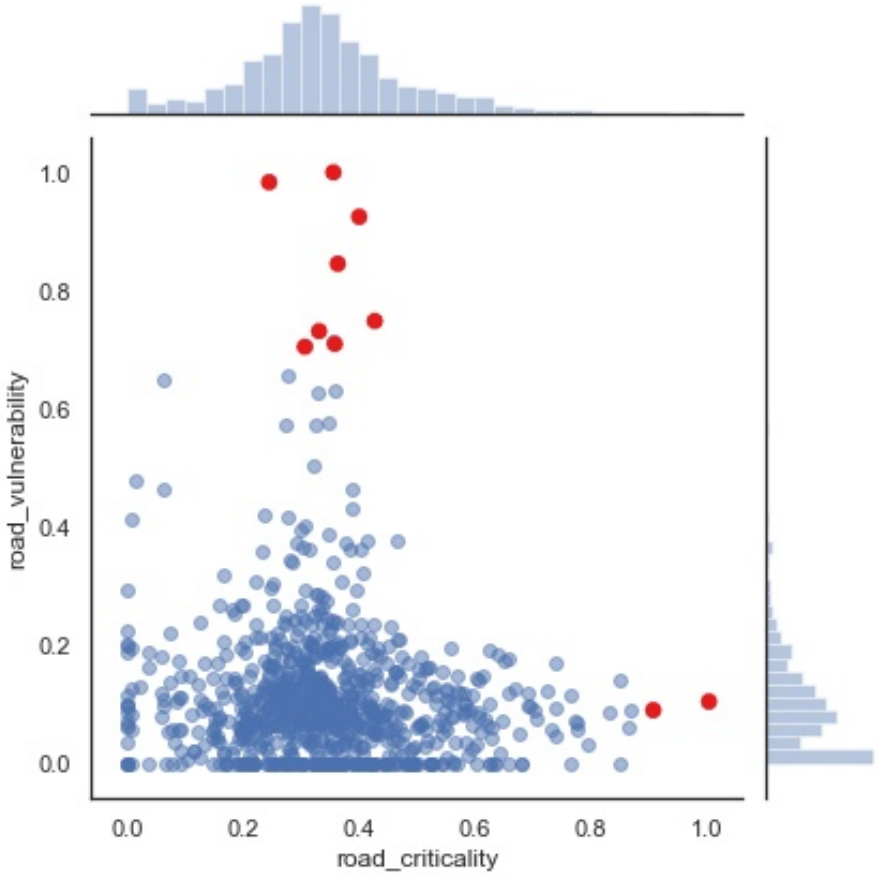

Figure 3.1: Criticality- and Vulnerability-index per road

3.1.1 Top 10 vulnerable and critical roads

The 10 roads that are most vulnerable are shown in table 3.1. In light of this information, it could be concluded that the roads listed below should have the most attention when investing in infrastructure. These roads have shown to be the most critical and vulnerable in Bangladesh.

Table 3.1: Top 10 most vulnerable and critical roads

Road	Criticality index	Vulnerability index
Z6806	0.35	1.00
Z5006	0.40	0.92
Z1036	0.24	0.99
Z7717	0.36	0.85
Z3704	0.43	0.75
N1	1.00	0.10
Z1031	0.36	0.72
Z5032	0.33	0.73
Z4606	0.31	0.70
N5	0.91	0.09

3.2 Vulnerability/Criticality-index per N1 road segment

To give the government of Bangladesh a closer look into which road segments are important a deep-dive analysis was done. Since this concerns an example the analysis is done for one road. However, the code is written so it is applicable for all roads in Bangladesh.

The road chosen for the deep-dive analysis is road N1, since the analysis of this road can give the most divergent results due to it's length. Road N1 consists out of the most segments of all roads in Bangladesh and therefore gives interesting results in the segment analysis.

The vulnerability index and criticality index per road segment of road N1 are plotted in the graph shown in fig. 3.2. Important to note for the government of Bangldesh are the two dots in the left corner. These two segments are by far the most vulnerable, but have a low criticality. The government can conclude that the two most vulnerable segments of the most important road of Bangladesh are not of great importance to the cargo transport. Instead, they can focus their attention to the six segments in the right upper corner of fig. 3.2.

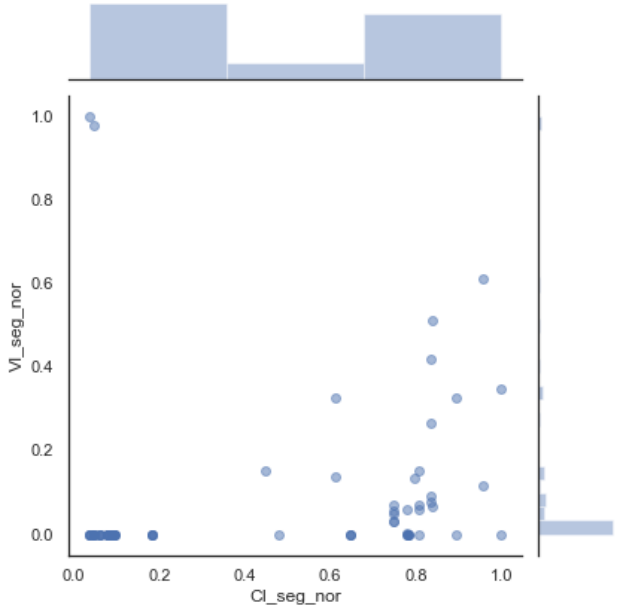

Figure 3.2: Criticality- and Vulnerability-index per segment of road N1

Chapter 4

Conclusion & Recommendation

Bangladesh has many vulnerable roads in terms of risks of bridges breaking down in case of disasters or hazards. The number of bridges in Bangladesh is known to be very high and some are in a poor condition. Even though the number of roads with a high vulnerability could be considered problematic, most of roads score low on the criticality-index. This indicates there are only a few roads in Bangladesh that undergo high traffic density. As shown in chapter 3 N1 and N5 are roads that carry a heavy traffic duty. This is also clearly shown in chapter 2 where the roads are visualized.

Based on both criticality and vulnerability, Z6806 is the road that is the most in need of investment. The vulnerability of this road shows the highest normalized value, while besides it seems a lot of goods transportation is going on this road. When bridges on this road are damaged, the economic consequences are expected to be significant.

It is recommended to the government of Bangladesh to invest in the reinforcement of bridges with a C or D condition on the roads Z6806 and Z5006. Consequently, this will lead to an improvement of the vulnerability of the road for disasters. Also will the improvement reduce the economic effects on cargo transportation.

The recommendations regarding the identification and visualization of the roads in Bangladesh are as follows:

1. For a more complex analysis of traffic density for criticality was no room during this assignment. Advised is to take a closer look at other forms of traffic instead of just trucks. This will give a more complete view of the criticality of certain roads.
2. Other factors could contribute to the criticality, such as the number of lanes and length of each segment. This provides an index based on the criticality per kilometer and could provide information about roads that need broadening for example.

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