Evaluating Reliability, Resiliency and Vulnerability
of
Urban Expressway

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APPROVAL

The dissertation entitled "**Evaluating Reliability, Resiliency and Vulnerability of Urban Expressway**", by Md. Nabil Zawad has been approved fulfilling the requirements for the Bachelor of Science Degree in Civil Engineering.

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DECLARATION

I hereby declare that the undergraduate research work reported in this thesis has been performed by me under the supervision of Assistant Professor Dr. Moinul Hossain. I have exercised reasonable care to ensure that this work is original and has not been submitted elsewhere for any purpose.

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ABSTRACT

The trend of increasing transportation demand with limited road network needs an exploration of evaluating performance of a transportation system. A transport network is a place where various interactive situations occur that arise complexity in a system. In such a system, urban expressways play an important role by reducing some of the variability associated with travel time by directly connecting major attraction and production zones. However, they are expensive and thus, limited in number and with sparse space to accommodate a high proportion of transport vehicles, some questions may arise that how often an urban expressway may fail, how quickly it recovers from the unstable states and how severe the consequences of failure of that system may be. Although there have been some research on estimating the vulnerability of transportation networks, the effort to evaluate the reliability, resilience and vulnerability (R-R-V) of an urban expressway in isolation has not been explored. This study presents an analogy between urban expressways and water stream and applies the popular methods used in water resource engineering to evaluate the R-R-V of urban expressways. For this, it selects Shibuya 3 route of Tokyo Metropolitan Expressways Company Limited as study area, which is heavily instrumented with detectors with an almost uniform spacing of 250 meters. . Six month data on traffic flow variables, e.g., speed, flow and occupancy for every minute for every detector location, along with road crash data were collected. R-R-V were calculated by comparing the quality of traffic stream density with the jam density of the respective location where any density below jam density was identified as satisfactory operational condition. R-R-V provides one of the most comprehensive approaches for analysing the probability of success or failure of a system, the rate of recovery of a system and to quantify the expected consequence of being in unsatisfactory states. The result from reliability heat map, resiliency and vulnerability curve advocates that there is high sensitivity (chances of system failure) in on-ramp, off-ramp zones of the route network. Due to congestion and crashes, system recovery rate is very much lower in connectors as it hampers traffic flow in both ways. These findings can be valuable in the

evaluation and selection of alternative design and operating policies for a wide variety of transportation system performance with a variety of operating policies.

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LIST OF ACRONYMS

CAR	Conditional Auto Regressive
DUI	Driving Under Influence
GLMM	Generalized Linear Mixed Models
PRT	Perception Reaction Time
R-R-V	Reliability-Resiliency-Vulnerability
SLR	Simple Linear Regression

LIST OF NOTATIONS

q	Traffic Flow
V	Vehicle Speed
K	Traffic Density
Kj	Jam Density
Kc	Critical Density
V_f	Free Flow Speed
Y	Dependent Variables
X	Independent Variables
b	Slope of Line
a	Vertical Intercept
$\propto$	Reliability
t	Time
S	Satisfactory Outputs
Γ	Resiliency
$E[T_F]$	Expected Time Length in Failure
A	Total Time in Failure Zone
B	Number of Occurrence in Failure Zone
F	Unsatisfactory Outputs

Chapter 1

Introduction

1.1 Background

Urban expressway, often known as controlled-access highway plays a dominating role as traffic artery in metropolitan cities by offering large capacity traffic service in multi-lane (both direction) with high speed uninterrupted flow (Jing et al., 2013; Yan and Du, 2009; Roess et al., 2011). It reduces travel time and connects major trip attraction and production zones. As rapidity and continuity are two main functions, urban expressway reliability is described by the probability of velocity above the certain threshold (Yan et al., 2016) whereas density is considered as a measure of effectiveness to define levels of service (Roess et al., 2011).

Complex variables often impedes the free flow of vehicles thus makes the system unreliable. Traffic congestion and road crash are two indicators of unreliability that eventually leads to various losses; losses of life, money and time. As urban expressway caters for a large number of commuters during peak hours, high congestion frequently interrupts the continuous flow (Wang et al., 2009). Also research by Shi et al. (2016) shows that crashes are more likely to occur on those congested segments during the peak hours. They have also found that frequent merging and diverging in auxiliary lanes pose a threat to mainline traffic of expressway thus raise the chance of crashes. To mitigate disruption and accidents, measures should be taken to preserve the potentiality of an urban expressway. In pre-construction phase, proper decision making is required to verify the feasibility before approving the design to keep the urban expressway fully operational. Traffic characteristics should be analyzed for specific conditions to predict and ease the decision making. In construction and post-construction phase, land utilization, design planning and law enforcement should be carried in such way that it fulfils the demand, controls the flow distribution on peak hours, avoids traffic pressure in expressway and parallel roads and restricts direct residential access. Also balancing on and off ramp, proper use of horizontal curvature, use of sign and marking are required to avoid road crashes (Yan and Du 2009; Shi et al., 2016).

In analyzing traffic flow characteristics and other factors associated with transportation system, many researches are often conducted using concepts from water resource management as because traffic flow exhibits similar behavior of fluid flow. Within the threshold limit traffic model predicts uniform traffic flow like fluid particles and becomes unstable above the critical limit (Flynn, 2009). Many macroscopic models were developed with the 'fluid-alike' concept since 1970. PW model was the first one by Payne and Whitham (Whitham, 2011) which drew similarities between the flow of fluid and traffic.

Whether to improve the existing scenario or to develop a new project, the behavior of the transport system should be known. The behavior should answer how the system is (or will be) performing and reacting to the severity. Fluid models can be used to evaluate the performance of a transport system. Statistical approaches are often taken on account for risk based indicators to measure the likelihood of failure, robustness and reliability associated with the water resource management system (Hoque et al., 2012). One of the highlighted work to mention here is by Hashimoto et al. (1982) which offered an opportunity in hydrology and water resource engineering to consider reliability, resilience and vulnerability (R-R-V) altogether as an indicator of system performance evaluation later on. Kjeldsen and Rosbjerg (2004) used the similar method in reservoir management and water supply systems. The approach was also adopted to evaluate the performance of the proposed Brahmaputra barrage in Bangladesh by Mondal et al. (2010) to meet the future water demand. These three indicators (R-R-V) can measure system characteristics and performance by analyzing dataset for certain conditions.

1.2 Problem Statement

Considerable amount of researches were conducted to evaluate transport system performance over the past decade since Berdica (2002) reviewed the road transport vulnerability literature. Most works have focused on individual criteria or indicators to evaluate the scenario. Reliability of a road network is often calculated based on different concepts; travel time reliability (Taylor, 2013; Pulugurtha and Duddu, 2014), uncertain based reliability (Soltani-Sobh et al., 2015), capacity reliability (Chen et al., 2002) etc. To assess the vulnerability of a transport system researchers have calculated vulnerability index by taking link capacity, travel time and alternative routes in account (Murray-Tuite and Mahmassani, 2004). Connors and Watling (2015) introduced a demand based vulnerability. Resilience has mostly covered its ground with vulnerability to differentiate the post disruption situation. D'Lima and Medda (2015) measured resilience by analyzing diffusive effects of failure. Tamvakis and Xenidis (2012) used the theory of entropy to evaluate transportation resiliency. All these works are network-based; however, from the perspective of the expressway operator, they may want to calculate these three indicators for their own infrastructure as variables considered for network-based system may not effectively work for urban expressways. A new approach can be taken to evaluate performance indicators only for urban expressway.

Reliability, resiliency and vulnerability are applied to relate the transitional movement of a transport system to the state of shock (Reggiani et al., 2015). To present the overall scenario interpretation between system stability (reliability), the consequences of system failure (vulnerability) and recovery rate (resilience) is needed. Seeliger and Turok (2013) judged resilience as the converse of vulnerability and stated *slight* difference between them. Also in the long run, resilience approaches as the probability of performance being satisfactory thus equals system reliability (Hashimoto et al., 1982). So, resilience can act like a bridge between reliability and vulnerability. Furthermore it can be demonstrated that R-R-V must be considered altogether to measure the performance of urban expressway.

Lack of previous works to measure R-R-V altogether for urban expressway has led an opportunity to present a new work here. Also it can be explored whether the widely used methods for calculating R-R-V in the field of water resource engineering can be applied for urban expressways as well.

1.3 Purpose and Objectives

The purpose of this research is to develop a framework to calculate reliability, resiliency and vulnerability of urban expressways and visualize results for easy decision making.

The specific objectives are to: (1) measure reliability, resiliency and vulnerability for urban expressways; (2) visualize the results for easy decision making.

1.4 Scope

The main scopes of this study is to study reliability, resiliency & vulnerability of one selected route of Tokyo Metropolitan Expressways Company Limited. There are several methods available to calculate these indicators, however, this study follows the methods by Hashimoto (1982) for measuring reliability, resiliency and vulnerability.

Chapter 2
Literature Review

2.0 General

This chapter provides a summary of all the major concepts and developments needed to be known for understanding the insights of this thesis.

2.1 Uncertainty in Transport System

A transportation system comprises of five primary components: commodities, fleet, infrastructure, freight and passengers (Ibanez et al., 2016). Therefore complexity and interdependency of transport components increase the sensitivity and uncertainty of a system. To minimize costs, infrastructure systems are often designed to work close to the capacity having little redundancy and reserved options which tends to supply-demand imbalance, technical disruptions, technical failure and natural disasters. Thus uncertainty can lead to system failure or break down. Accidents, congestion, infrastructure collapse or unwanted disruption (antagonistic or terrorist attacks) may lead to injuries, fatalities, social and economic loss. Also cost of repairing or rebuilding a reliable infrastructure will be significant (Mattsson and Jenelius, 2015). Transport system may also fail if capacity utilization is increased (Goldberg, 1975). Therefore to analyse traffic system uncertainty distinction between losses of transport assets, service disruption, interruptions in operations and their short and long term consequences should be considered (Hallegatte, 2014).

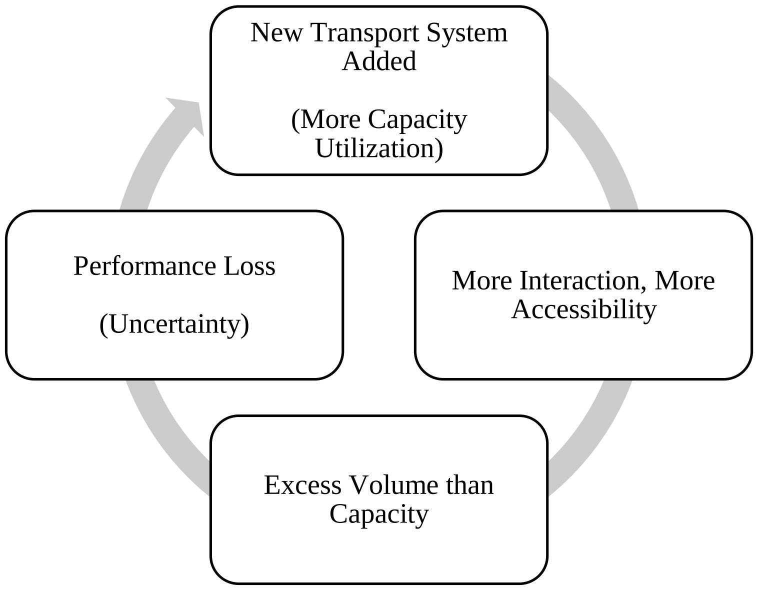

Figure 2.1: System Uncertainty on Capacity Utilization

(Source: Reproduced from Goldberg, 1975)

2.2 System Performance Evaluation

2.2.1 Current Practices

To evaluate transport system performance, in terms of methodology, Poisson models are often used. Fosgerau and Engelson (2011) showed that irrespective of the form of distribution of trip destinations, the maximal expected utility is a linear function of mean and standard deviation. Therefore, including the standard deviation of duration in the cost function is an adequate measure of reliability. Watling and Balijepalli (2012) also used mean and variance of travel time when assessing road network vulnerability. However one of the demerits of calculating mean and variance as a performance indicator is that variance of crash data may sometimes rise significantly higher than the average (mean) and the output can show insignificant changes if a longer time span is considered (Hashimoto et al., 1982; Sun et al., 2016). Poisson-gamma (also known as negative binomial) models have also been applied (Malyshkina and Mannering, 2010; Gomes, 2013) in alteration of Poisson models to adapt the over-dispersion of crash data. These conventional models fail to capture the spatial fluctuations among roadway segments thus leads to inappropriate estimation. Several models considering spatial effects were developed later on. Li et al. (2007) developed a conditional autoregressive (CAR) model to analyse motor vehicle crashes. Miaou and Song (2005) showed how multivariate spatial generalized linear mixed models (GLMM) can be used to model traffic crashes and significantly improve the overall model goodness-of-fit. In recent studies (Mitra and Washington, 2007; Aguero-Valverde, 2013) Bayesian approach has become popular as it can handle complex models.

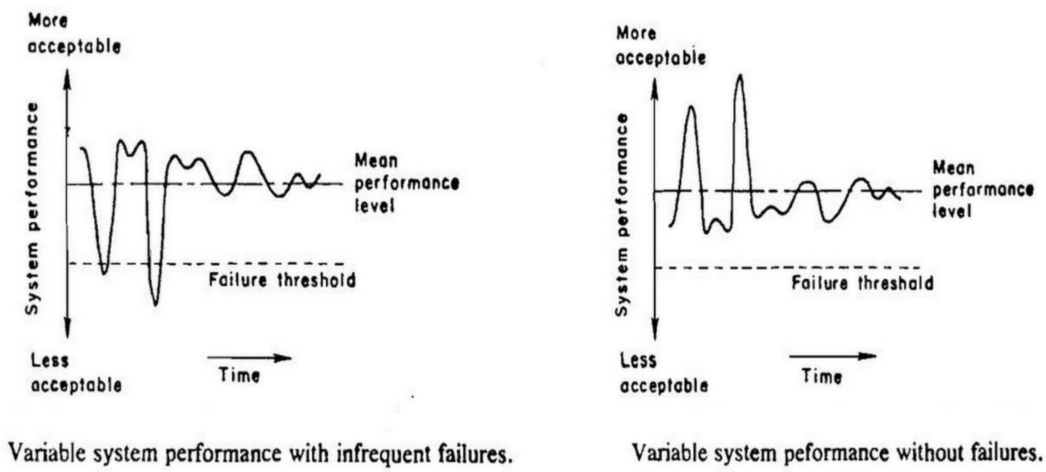

Figure 2.2: Inaccurate Evaluation by Mean-Variance and Poisson Models

(Source: Hashimoto et al., 1982)

2.2.2 Introduction of Three Performance Criteria

2.2.2.1 Reliability

Reliability is defined as the probability that a system will perform functionally (without failure) for a given period of time in any condition (Ebeling, 2004). As high traffic congestion started questioning the stability of a road network, research works on transport system reliability began after 1980s. The opportunities of capturing instant and continuous travel time, occupancy and speed data have flourished the possibility of predicting reliability of transportation system (Pulugurtha and Duddu, 2014). Measure of reliability depends on many factors: situation, level of appliance, available resources and so on. Many research works are conducted on reliability models based on different factors. Soltani-Sobh et al. (2015) presented a reliability model (uncertain based model) using three performance functions- the total travel time, flow and customer surplus. Reliability can also be analyzed by examining the links between travel time uncertainty and the effect on departure time choice (Noland and Small, 1995). Road capacity is often analyzed to meet the demand, a concept of capacity reliability by Chen et al. (2002). Recent research on transport system reliability has focused on the performance of a system under capacity or demand fluctuations (Taylor, 2013).

2.2.2.2 Vulnerability

Vulnerability deals with the severity of consequences when a system goes to failure condition (Hashimoto et al., 1982). A proper definition of vulnerability for transportation system can be cited from Berdica (2002), as stated: *"Vulnerability in the road transportation system is a susceptibility to incidents that can result in considerable reductions in road network serviceability."* For the past two decades it has become a significant research topic in the field of transportation. Nicholson and Du (1997) published one of the first transport studies that introduces vulnerability. They suggested that unreliability comes from two variations- demand (or flow) variations and supply (or capacity) variations. Several researches have contributed to measure vulnerability index. Murray-Tuite and Mahmassani (2004) introduced a vulnerability index on the basis of traffic flow, link capacities, travel times and the availability of alternative routes. Scott et al. (2006) proposed a Network Robustness Index to find sensitive links of highway network. Chen et al. (2007) calculated consequences by proposing a utility-based accessibility measure. Dehghani et al. (2014) carried a vulnerability study that combines topological-based measure (i.e., graph theory) with a system-based measure (i.e., travel demand and supply data). Vulnerability can be analysed from the viewpoint of shock propagation. In this respect Vermeer (2012) considered and analysed three dimensions of a shock (depth, width and strength) by identifying different features of contagious effects. As demand variation in road network can increase the transport system uncertainty, Watling and Balijepalli (2012) developed a method to separate the effect of demand growth on the mean, variance and skewness of travel times to identify the most vulnerable links of a network. Whereas present researches focus on the probability of damage and variation in traffic demand to measure vulnerability, Liu et al. (2016) established a new theory, using a system-thinking approach to identify high-consequence failure scenarios that may arise from vulnerable weakness in the form of the network which are independent of traffic demand models or source of damages. It is necessary to determine a system's vulnerability to help decision makers on applying policies and design a flexible network to mitigate traffic congestion as well as to improve the transport system performance.

2.2.2.3 Resiliency

A robust transportation system must: a) absorb effects from disturbances and b) ensure operational continuity. The design of resilience can make sure these requirements are fulfilled (Tamvakis and Xenidis, 2012). The concept of resiliency can be described through vulnerability. When a system becomes vulnerable it will fail (i.e., reduction of performance) at some point. So the system must bounce back to a position that is serviceable or workable to perform as required. Resiliency is the measure of time to absorb the shock (failure) once it occurs and recover quickly after the shock (Bruneau et al., 2003; Hashimoto et al., 1982). Dekker et al. (2008) proposed a working definition of resilience: *"A resilient system is able effectively to adjust its functioning prior to, during, or following changes and disturbances, so that it can continue to perform as required after a disruption or a major mishap, and in the presence of continuous stresses"*. In transportation system, one of the most popular measures of resiliency is given by D'Lima and Medda (2015). They used a mean-reverting stochastic model to analyse the diffusive effects of failure. The parameter can capture the rate of recovery of a system after it is subjected to random shocks. Tamvakis and Xenidis (2012) proposed a conceptual framework to evaluate transportation resilience by utilizing the notion of entropy. Proper evaluation of performance often depends on the resiliency of a system.

2.3 Traffic Flow Variables

To study microscopic traffic stream parameters the relationship between three principle variables (flow rate, speed and density) must be established. To characterize the relation between these parameters researchers often use a traffic flow fundamental diagram. Several researches have been conducted on single-regime models (i.e., single functional form of speed-density models) by developing traffic flow theories. Traffic flow theories contribute in analysing shock wave propagation characteristics and traffic flow stability (Xu et al., 2014). The first and one of the most popular speed-density models was presented by Greenshields et al. (1935) around 80 years ago. The model demonstrated a linear relationship between speed and density. The model also presented an idea to formulate speed-flow and flow-density relation from the speed-density relation. Following the steps of Greenshields model many researchers have developed and modified the traffic flow model later on. Greenberg (1959), Underwood (1961), Bell shaped curve (1967) and Pipes-Munjal (1967) are some remarkable models to be mentioned here. Greenberg (1959) established a non-linear relationship by developing a bridge between macroscopic stream model and microscopic car following model. The main drawback of this model was the inability to predict speed at lower densities. Underwood (1961) tried to overcome the problem and derived an exponential model. One of the demerits of Underwood model is that speed becomes zero at high densities. Hence the model fails to predict speed at high densities. Later, Pipes (1967) modified the Greenshields' model to enhance the accuracy. Recent traffic models (usually known as modified speed-density relationship) mostly follow the classical models discussed above.

Traffic flow relationships are established based on field-data. Significance of traffic models mostly depend on proper data collection. Modern sensor technologies have the ability to detect the presence of vehicles and thus captures speed and density data. In practice, inductive loop detectors are widely used on highways worldwide to capture vehicle speed since 1990 (Soriguera and Robusté, 2011). Aboveground sensors can be used as an alternative reliable and cost-effective vehicle tracking system of loop detectors. Video image processors, microwave radar, ultrasonic are some of the aboveground sensors installed along roadway that can capture density, travel time and origin-destination pairs (Mimbela and Klein, 2000). Availability and accuracy of real-time traffic flow data is important to correlate the relationships between speed, flow and density.

Chapter 3
Methodology

3.1 Introduction

The research followed a series of steps to fulfil the stated objectives. At first jam density was calculated from the sorted detector data by using Greenshields traffic flow model. Then critical density was calculated for each jam density. After that reliability, resiliency and vulnerability (R-R-V) were measured by using certain conditions for critical density and established formulas given by Hashimoto et al. (1982). The overall workflow is explained in Figure 3.1.

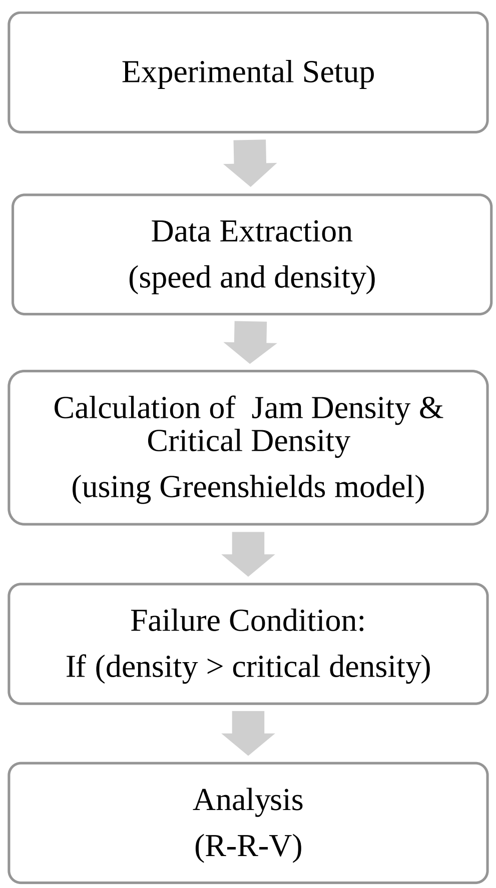

Figure 3.1: Methodology Workflow

3.2 Study Area and Data Extraction

3.2.1 Study Area

For the purpose of the study, Shibuya 3 route (also known as “Shuto Expressway 03”) of Tokyo Metropolitan Expressway, Japan was chosen as the study area. The route is situated in the centre of Tokyo Metropolitan area connecting and covering important business and residential areas. The length of Shibuya 3 is 11.9 kilometres. It is heavily instrumented with vehicle detectors having homogeneous spacing and excellent accuracy. A schematic diagram of the routes is provided in Figure 3.2 (not drawn to scale). Frequent system collapse (congestion and crashes) had made the area suitable for the research work.

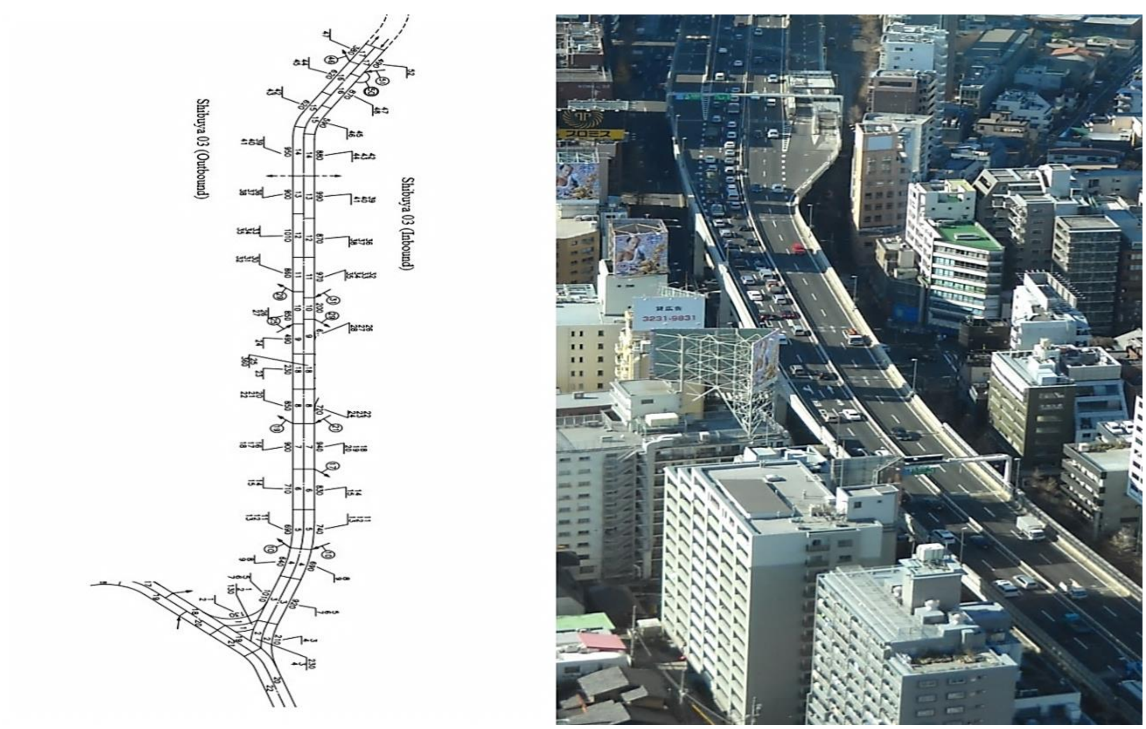

Figure 3.2: Shibuya 3 route of Tokyo Metropolitan Expressway

(Source: Tokyo Metropolitan Expressway Company Limited)

3.2.2 Data Extraction

The study covered only the inbound direction of Shibuya 03 route. 35 uniformly spaced detectors having an average distance of 300 meters from each other were chosen to extract the data. In Tokyo Metropolitan Expressways, each detector captures data in every eight milliseconds. The authority aggregated the data in one minute for each detector and provided a complete dataset of 6 months (March 2014 to August 2014) to conduct the research. A map was also provided which includes information on location of ramps, detector positions and section length. Each detector captures data of speed, flow, occupancy and number of heavy vehicles (both lanes) for 24 hours a day in one-minute interval i.e., 264960 minutes (data) in total for 6 months. A schematic diagram is shown in figure 3.3 showing the detector layout.

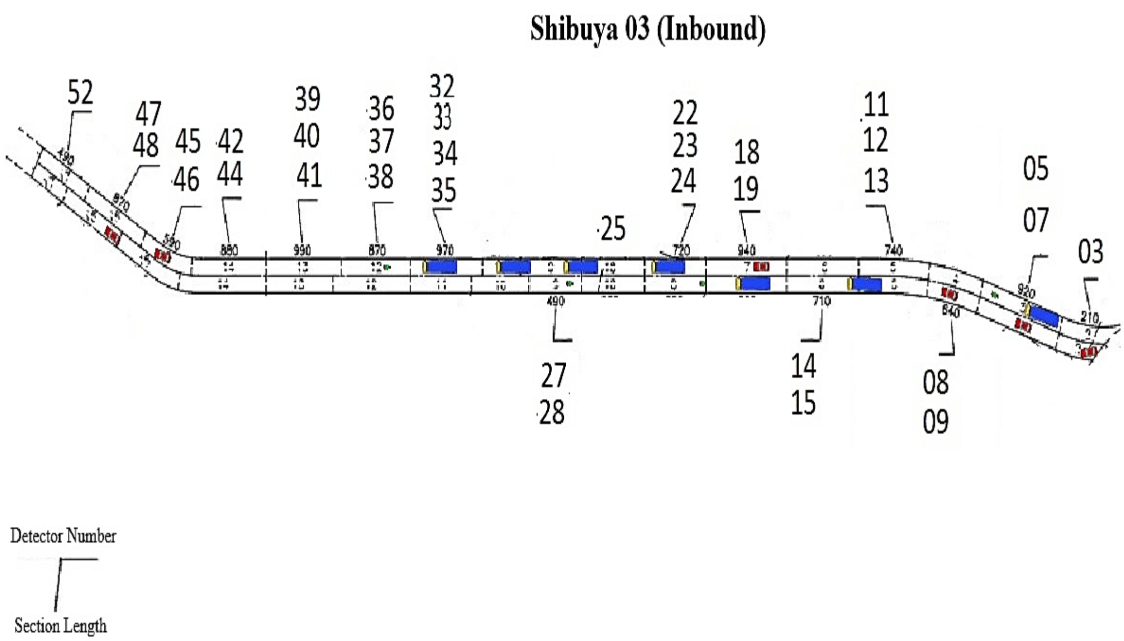

Figure 3.3: Detector Selection for Data Extraction

3.3 Data Preparation

3.3.1 Sorting Speed-Density Dataset

Traffic flow theories utilize speed and density as the input variables. Although the detectors provided speed and occupancy the result remained same as because existing literature suggests a linear relationship between density and occupancy if the proportion of heavy vehicles is low (around 8% in the chosen study area) and the detector length is roughly same (Kim and Hall, 2004). For each detector speed and density data were sorted out for 6 months to analyse detectors separately and compare length based traffic variation. Table 3.1 shows a sorted sample dataset of a detector. Here the units of speed and density are in kilometres per hour and percentage value respectively.

Table 3.1: Speed-Density Sorted Dataset (Sample)

Time Duration	Detector ID	Speed	Density
00:00-00:01	03-01-41-1	67.2	7.6
00:01-00:02		63.6	9.4
00:02-00:03		72.4	4.7
00:03-00:04		69.2	5.3
00:04-00:05		77.1	6.2

3.3.2 Speed-Density Relationship Model

Traffic flow theories follow the given fundamental relationship among three major variables flow (q), speed (V) and density (K):

$$q = V \times K \tag{1}$$

Equation (1) is used to generate relationship such as: speed-density, density-flow or speed-flow. After sorting speed-density dataset it was required to draw a relationship between those two variables to quantify jam density. As literature suggested a number of traffic flow theories, for this research purpose Greenshields Model was used to draw the speed-density relationship. The model given by Greenshields (1935) was of a ground-breaking significance and had been used widely, including in the Highway Capacity Manual 1965 edition and 1985 edition. The equation by Greenshields Model suggesting a linear relationship between speed and density is given below:

$$K = K_j \left(1 - \frac{V}{V_f}\right) \tag{2}$$

Where, K_j = jam density (when V = 0); V_f = free flow speed

Equation (2) provided the value of jam density which was needed to calculate the critical density for the given dataset.

3.3.3 Finalizing Datasets

3.3.3.1 Simple Linear Regression Analysis

Simple linear regression is a statistical method that allows correlation between two continuous (quantitative) variables. Among the variables, one denoted by *X* is regarded as the *predictor* or *independent* variable and the other denoted by *Y* is known as the *outcome* or *dependent* variable. Simple linear regression analysis produces a linear regression line:

$$Y = bX + c \tag{3}$$

Here, *b* is the slope of the straight line and *a* is the vertical intercept i.e., the point where the regression line intercepts the Y axis.

3.3.3.2 Linear Transformation of Greenshields Model

In order to run the regression analysis, the Greenshields formula presented in equation (2) was transformed to a linear form (shown in Table 3.2). The outcome of the regression analysis provided jam density (K_j) as the vertical intercept.

Table 3.2: Linear Transformation of Greenshields Model

<table>
<tr><th>Equation for Simple Linear Regression Analysis</th><th>Greenshields Model</th><th>Transformation of Greenshields Model</th></tr>
<tr><td rowspan="2">Y = bX + a</td><td>$K = K_j\left(1 - \frac{V}{V_f}\right)$</td><td>$K = \left(-\frac{K_j}{V_f}\right)V + K_j$</td></tr>
<tr><td colspan="2">K = density (dependent variable)
V = velocity (independent variable)
K_j = jam density (vertical intercept)</td></tr>
</table>

3.3.3.3 Critical Density and Its Relation with the Traffic Flow

Critical density is the outcome of ordinal differentiation of Greenshields model. If the equation (2) is rearranged it forms:

$$V = V_f - \left(\frac{V_f}{K_j}\right) K \tag{4}$$

Now substituting equation (4) in (1) and differentiating the new equation with respect to K for maximum flow will result in:

$$K_c = \frac{K_j}{2} \tag{5}$$

Here,

K_c = critical density i.e., density at maximum flow

The relation of K_c with traffic flow is that comparison between K and K_c provides the traffic condition for the given dataset of density. If a random density data crosses the value of critical density it signifies that the present condition has crossed the maximum allowable density limit and is moving towards a failure situation where congestion or crash is going to occur. The overall relationship between flow and critical density is shown in Figure 3.4.

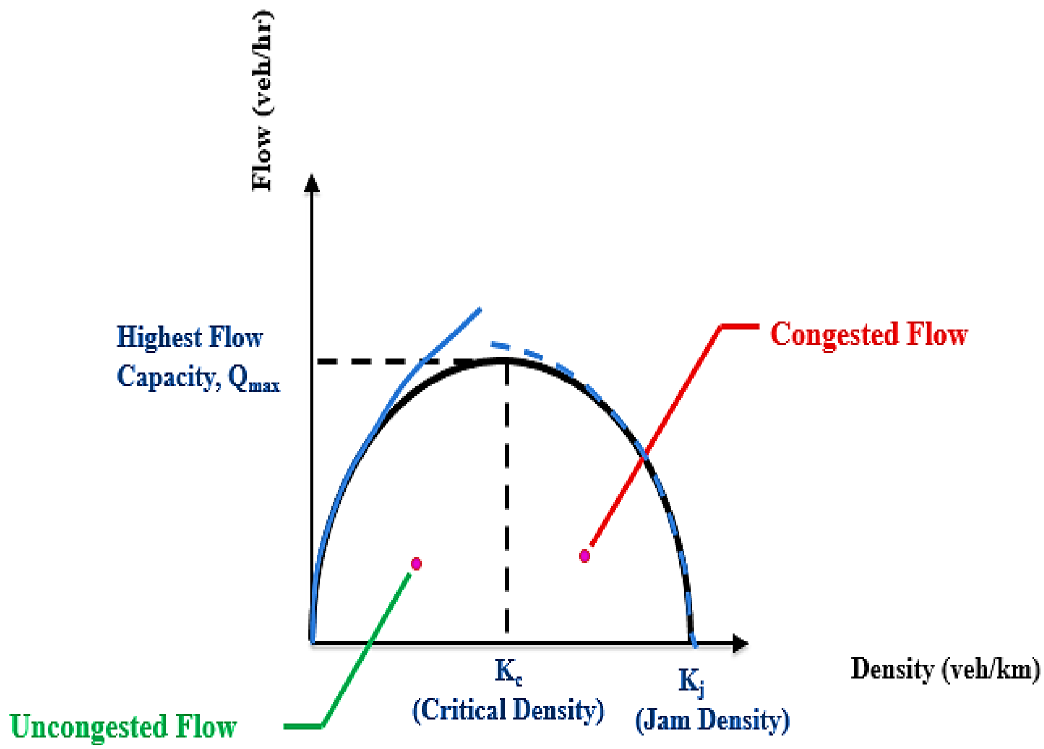

Figure 3.4: Traffic Flow-Critical Density Relationship

3.3.4 Calculation of Reliability, Resilience and Vulnerability

The method of calculating reliability, resiliency and vulnerability (R-R-V) - three system performance criteria was followed by the work of Hashimoto et al. (1982) which was applied in water resource system performance evaluation. Table 3.3 highlights the mathematical expressions used for the evaluation of R-R-V.

Table 3.3 Mathematical Expressions for Evaluating R-R-V

Performance Indicator	Mathematical Expressions	Significance	Remarks
Reliability	$\propto = \text{Prob} \{ X_t \in S \}$	The reliability of a system is described as the frequency or probability that the system is in a satisfactory state.	$\propto$ = reliability X_t = random variables at time *t* S = set of all satisfactory outputs ($K < K_c$)
Resiliency	$\Gamma = E [T_F]^{-1}$	If T_F is the length of time a system's output remains unsatisfactory after a failure, then the resiliency of a system can be defined as the inverse of T_F.	Γ = resiliency $E [T_F] = \frac{A}{B}$. Where, A = total time in failure zone B = the number of times the process went into failure zone
Vulnerability	$V = \sum_{j \in F} s_j e_j$	Vulnerability is the probability (e_j) of most severe outcome that occurs in a sojourn (s_j) into the set of unsatisfactory state.	F = set of all unsatisfactory outputs ($K > K_c$)

Chapter 4
Results and Analysis

4.1 Introduction

The results obtained through the previously outlined methodology are presented in this chapter. In order to visualize reliability a heat map was produced by using "R', a popular open source statistical analysis program (package names- dplyr, ggplot2).

4.2 Reliability

Figure 4.2 shows a heat map of Shibuya Route 03-01 explaining three phenomena reliability, risk and crashes occurring in the month April, 2014. Here, reliable zones are marked in yellow colour which satisfies the condition ($K<Kc$) and indicates that the system is in satisfactory condition. Risk zones are marked in red colour signifying unsatisfactory condition ($K>K_c$).

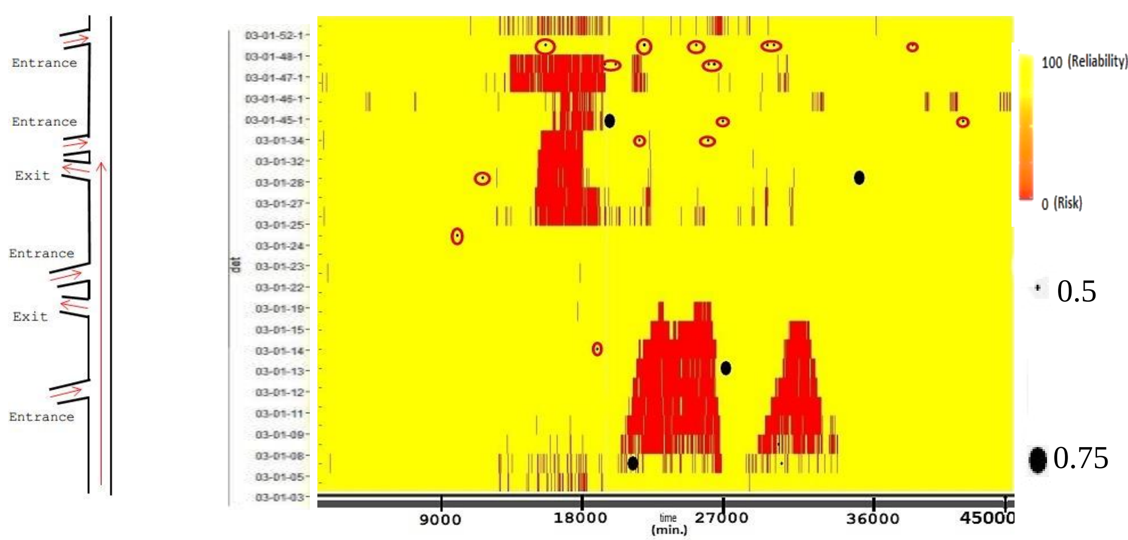

Figure 4.1: Reliability Heat Map (April)

In unsatisfactory conditions there are high chances of congestion and crash. In several situations, crash took place in both satisfactory and unsatisfactory conditions. To highlight its importance, two black points of different sizes were used. Thin points explains the occurrence of crashes in satisfactory conditions (reliable zones) whereas thick points explains the occurrence of crashes in unsatisfactory conditions (risk zones). In the diagram, x-axis represents the times in minutes and y-axis represents the detector spacing i.e., the expressway section. For a comprehensive visualization, a schematic diagram of the expressway is shown in the figure with on-ramp and off-ramp connectors. The heat map has shown high sensitivity (chances of congestion and crashes) in and around those connectors. The results have also showed large continuation (with respect of time duration) when the system entered into a risk zone. There were a few occasions where the risk zones continued for several minutes to few hours and resulted a crash.

Similar reliability analysis for March May, June, July and August are shown in figure 4.2, 4.3, 4.4, 4.5, 4.6 respectively. The analysis detected July, 2014 as the most congestion and crash prone month amongst the six months.

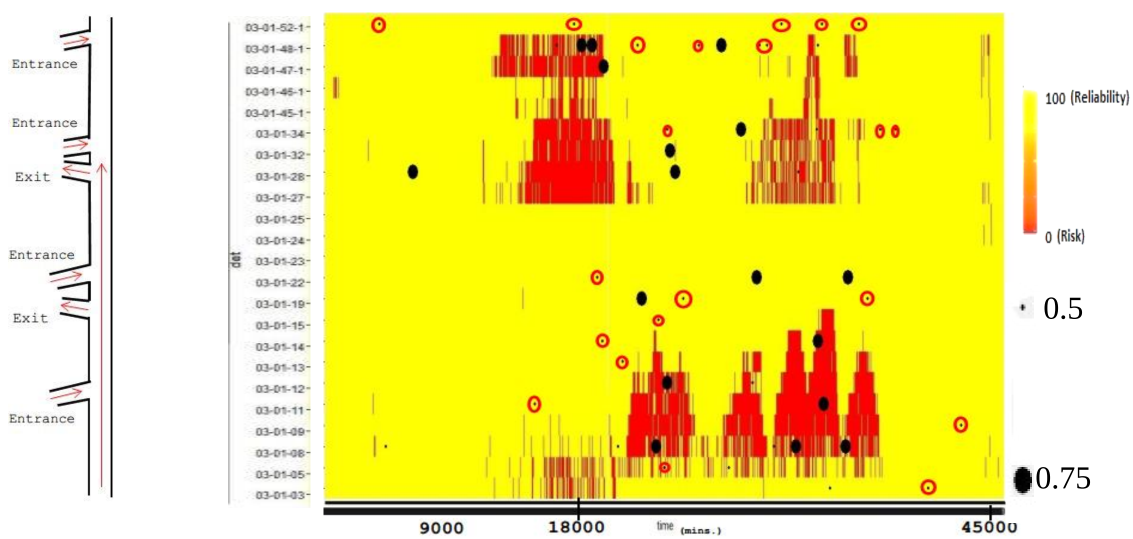

Figure 4.2: Reliability Heat Map (March)

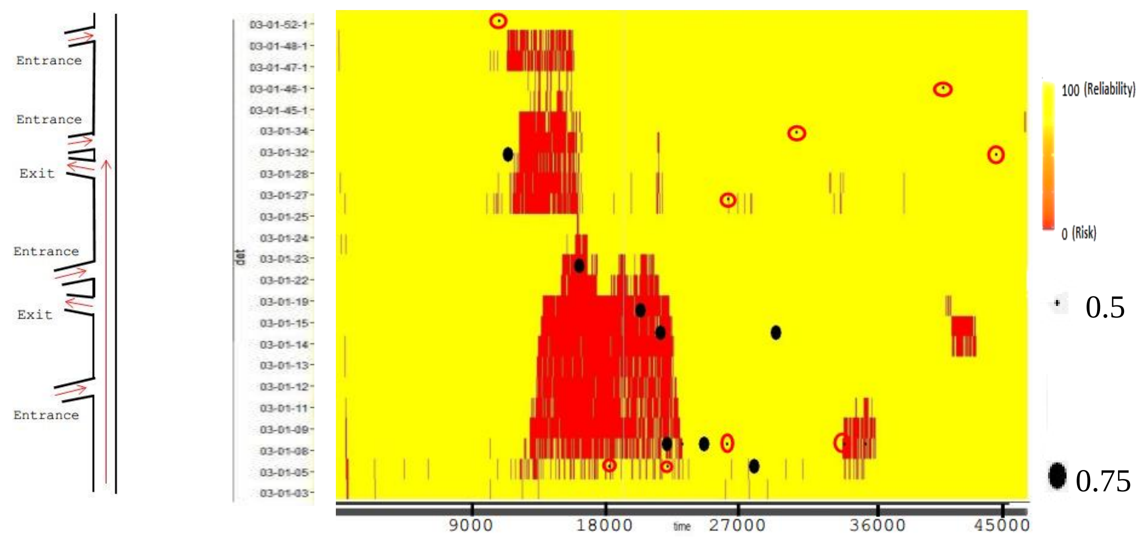

Figure 4.3: Reliability Heat Map (May)

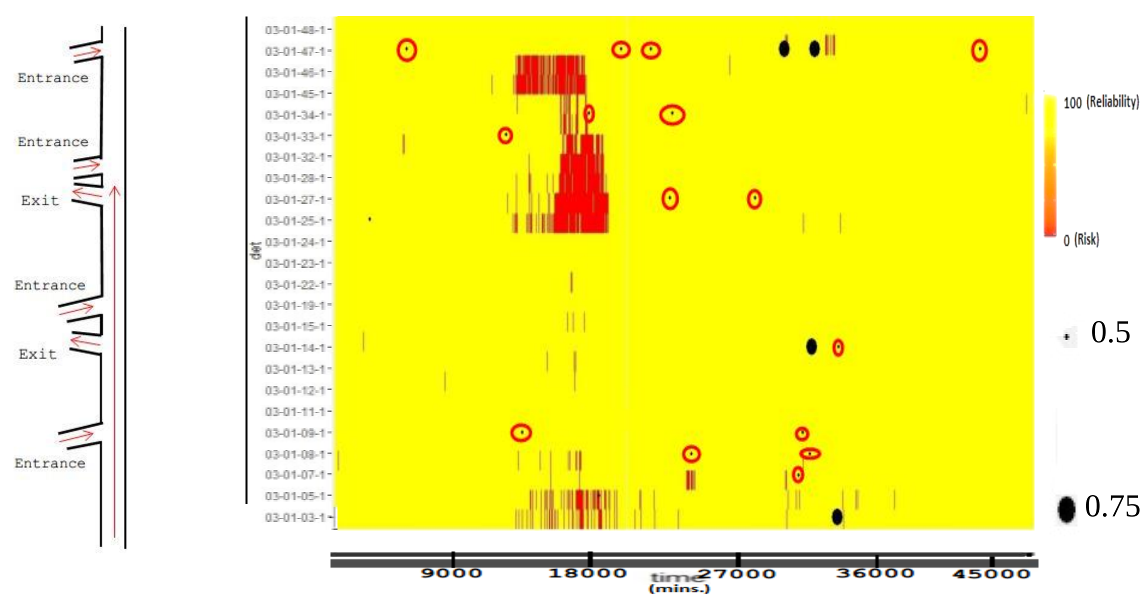

Figure 4.4: Reliability Heat Map (June)

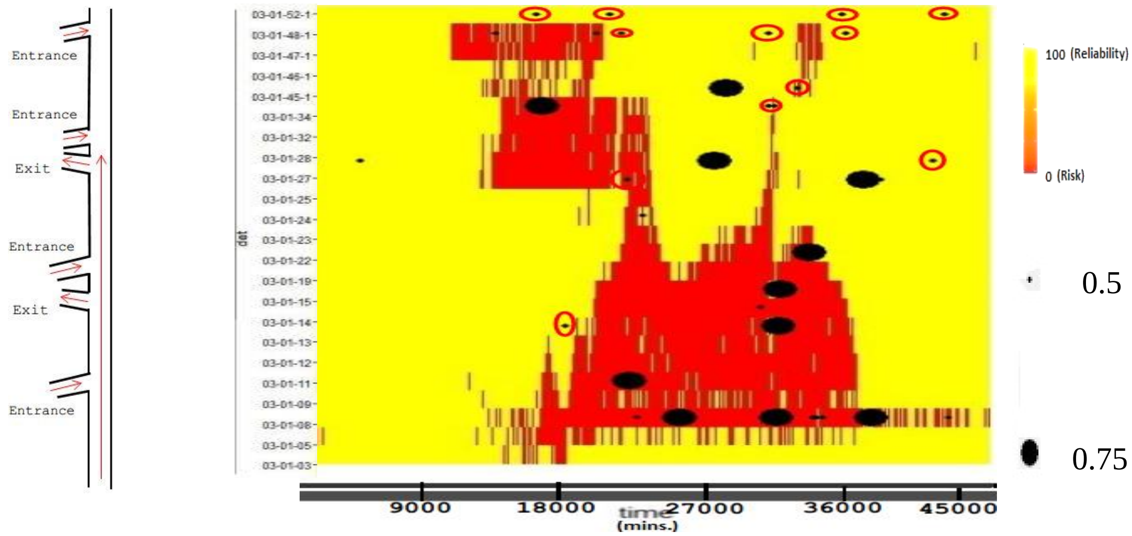

Figure 4.5: Reliability Heat Map (July)

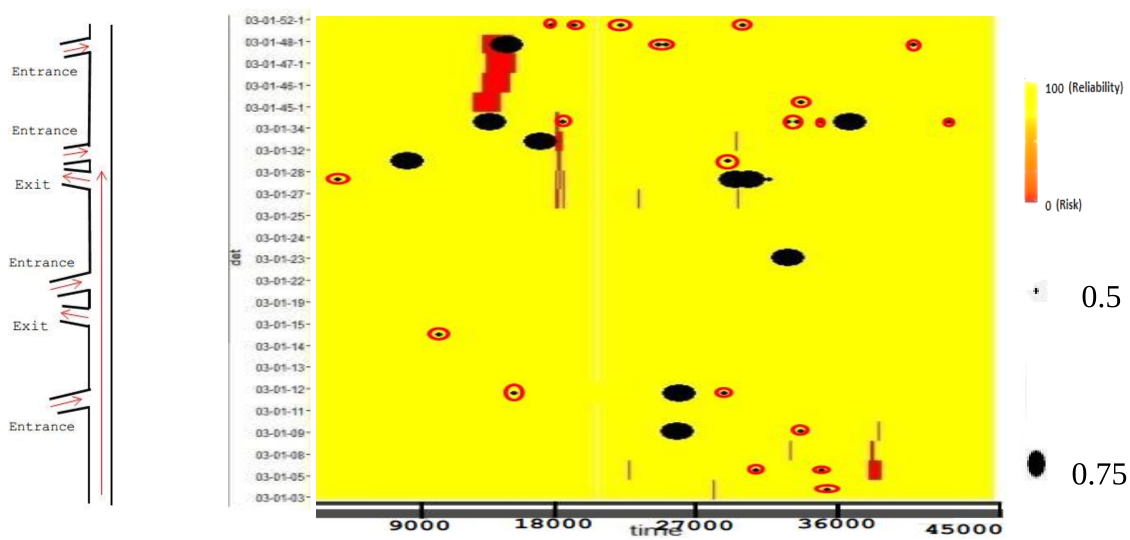

Figure 4.6: Reliability Heat Map (August)

4.3 Resiliency

To analyse the recovery rate of the system, a resilience curve was plotted against the detector spacing to establish an overall scenario on how the system reacts with the unsatisfactory situation and how fast the recovery rate was from the risk zone to reliable zone. Figure 4.7 shows the recovery rate of Shibuya Route 03-01 expressway during the month April, 2014. A schematic diagram of the route was also added.

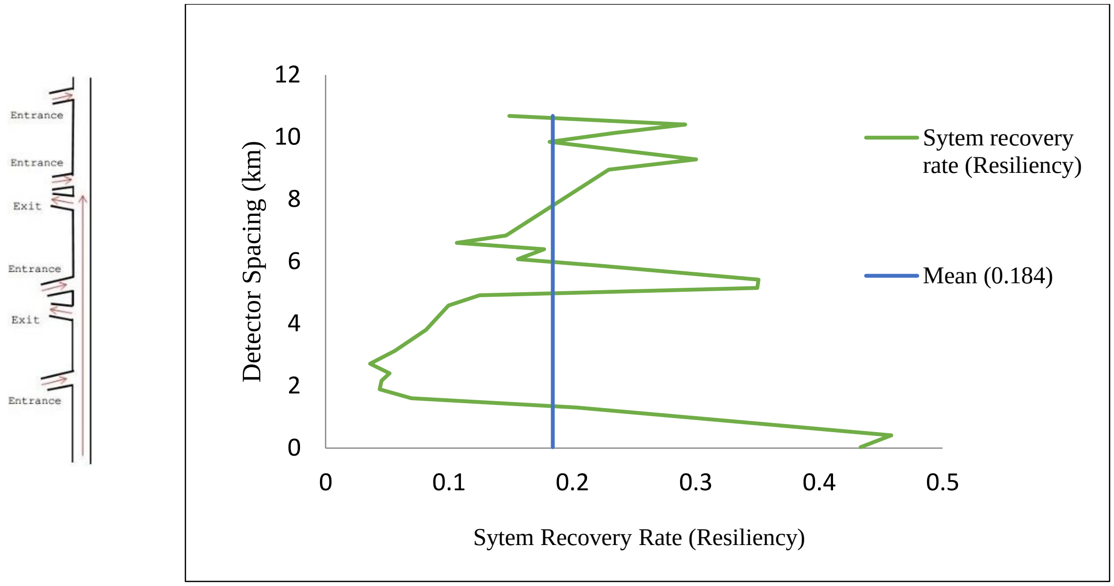

Figure 4.7: System Recovery Rate (April)

Value with higher resilience rate indicates the rapidity of recovery of the system in satisfactory state. The mean recovery rate for the route 03-01 throughout the month April was 0.184. The fluctuation around the mean value signifies the variation of recovery rate. The result showed very low recovery rate in on-ramp zones. The lowest recovery rate recorded was 0.036 at the entrance of first ramp and highest rate of recovery was 0.46. Observations showed better resiliency rate before a ramp entrance and after a ramp exit. Figure 4.9, 4.10, 4.11 and 4.12 shows the resilience curve for rest of the months. Again, July 2014 had the lowest overall (mean) recovery rate of 0.152 and August 2014 had the lowest recovery rate (0.021) at a distance of 2.71 km from the start.

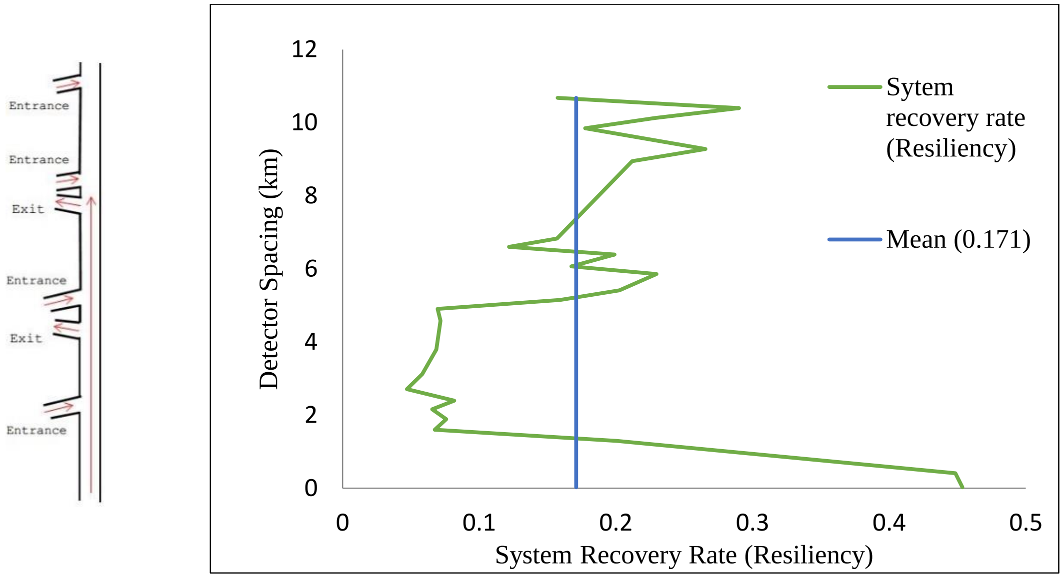

Figure 4.8: System Recovery Rate (May)

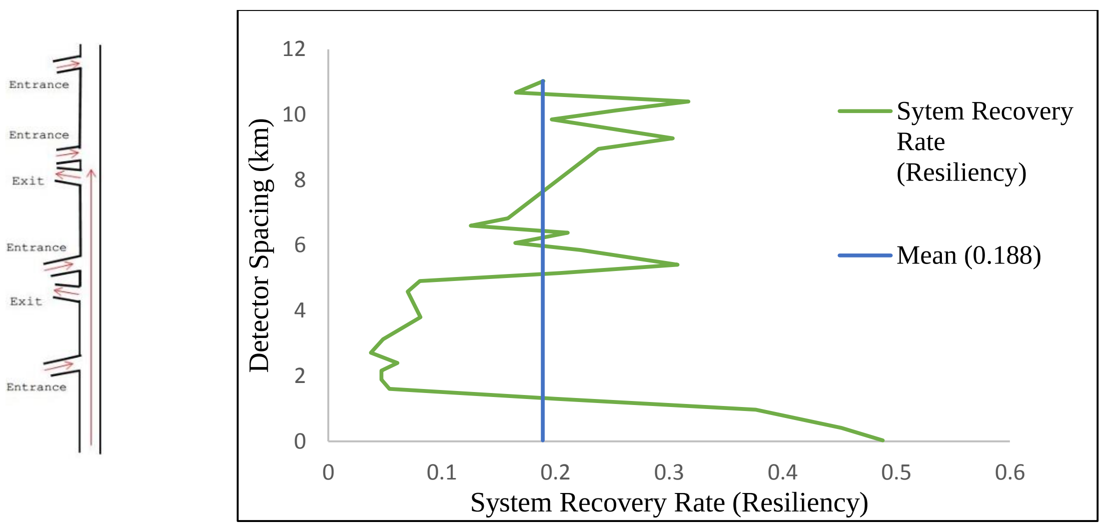

Figure 4.9: System Recovery Rate (June)

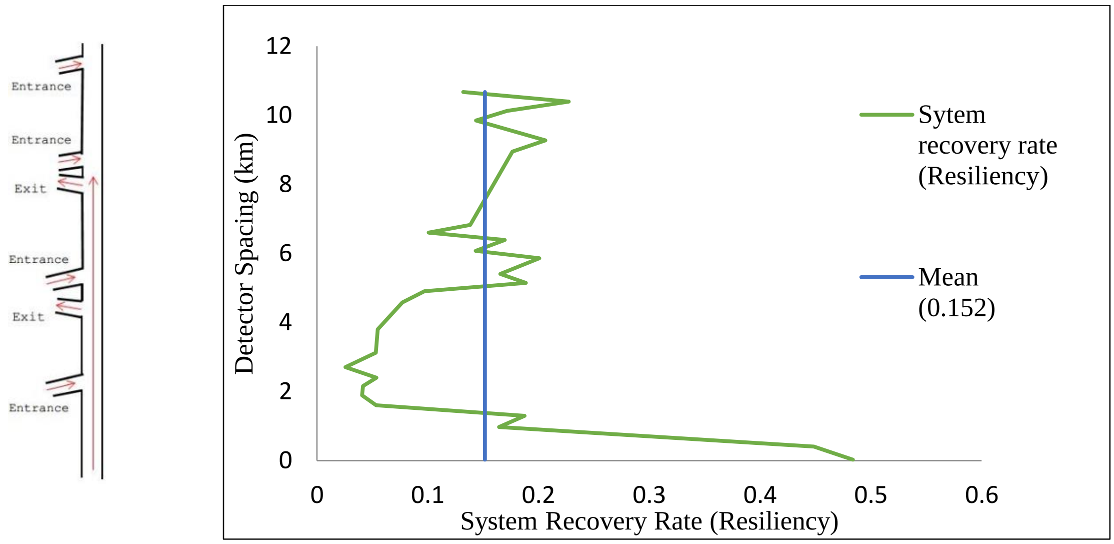

Figure 4.10: System Recovery Rate (July)

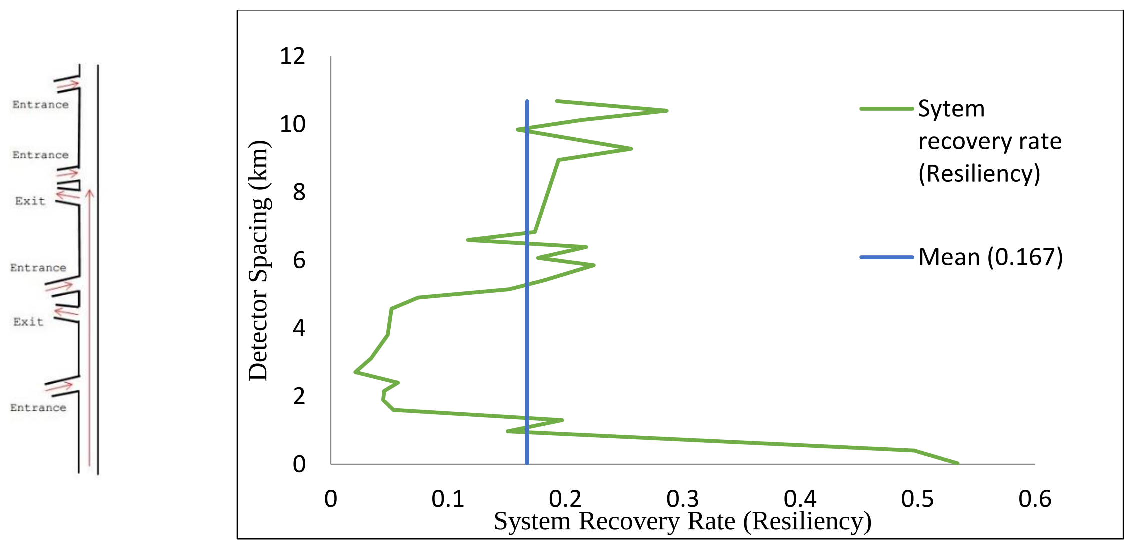

Figure 4.11: System Recovery Rate (August)

4.4 Vulnerability

Visualization of vulnerability shows the severity of consequences once the system enters the failure zone. For better representation vulnerability curve is presented in figure 4.13 for all six months as monthly variance would not be significant to visualize the overall vulnerability. Here, the mean signified the magnitude of vulnerability for the Shibuya Route 03-01 expressway. The highest magnitude of vulnerability was recorded as 40.35 at 6.07 km from the start which lies before an on-ramp. The value signifies that the performance of the expressway became more susceptible to congestion and crash before meeting the on-ramp.

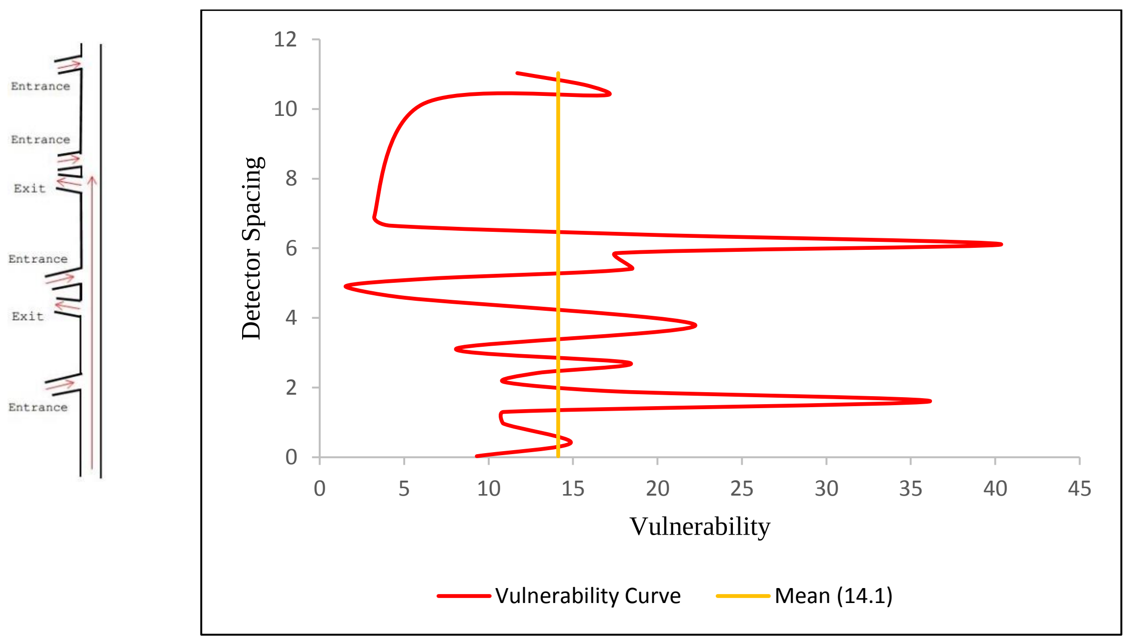

Figure 4.12: System Vulnerability (6 months)

Chapter 5

Conclusion and Recommendations

5.0 General

This chapter summarizes the key findings based on the pre-set objectives. This is followed by suggestions for future research scopes.

5.1 Introduction

The key objectives of this study were to establish a performance indicator framework for easy decision making by utilizing traffic detector data (velocity and density) placed on Tokyo Metropolitan Expressways by assessing the existing behaviour of Shibuya Route 03-01 expressway and use the findings for a new project or to modify any existing models. Urban expressways play a dominating role in urban city. As the characteristics of an expressway are different from a typical road network, proper study is required to find the causes and consequences of expressway system failure (congestion and crash). Lack of previous research in this regard had led an opportunity to produce this work. The end result of this research provides an incisive visualization of reliability, resiliency and vulnerability of urban expressway and provides a primary baseline for further research on urban expressways.

5.2 Discussion

A system is often built close to its capacity to minimize cost and space thus collapses whenever the capacity utilization exceeds the threshold. Urban expressways are one of the major means in transportation system in urban areas where daily vehicle volume remains significantly high. In spite of having the capability of receiving large vehicle capacity, expressways often fail to run smoothly because of over loading, especially in peak hours. The situation gets worsen in connecting zones where ramp volume meets the freeway volume. Findings of this study also suggest high congestion during peak hours and in ramp connectors. Crashes also influence congestion and vice-versa. Beside crash, impatience, frequent lane change, tolling system and temporary engine failure of vehicles also hampers free flow and influences high congestion. System recovery rate is much lower in congestion prone areas. Performance analysis also indicates low vulnerability in off-ramp connectors as recovery rate increases when an off-ramp releases the over capacity.

The analysis of reliability heat map highly recommends to keep an eye on the zones approaching near an on-ramp. The map shows high crash occurrence in risk zones where vehicle density is higher than the standard value. It also shows several crashes in reliable zones where free flow of vehicle prevails. Several factors influence these crashes. Crash data provided by the authority shows over speeding and unsafe driving as two main causes of the accidents. Continuous free flow allows over speeding. Over speeding reduces a driver's peripheral vision and increases perception reaction time (PRT) which results collision with the vehicle attempting to enter the freeway. Minor factors like maintenance fault, driving under influence (DUI), fatigue, impatience, age can also contribute to accidents. Crashes results a temporary system shut down and blocks vehicle flow in both freeway and connectors (ramp) and makes the system unreliable, decreases recovery rate thus makes the system more vulnerable.

The overall comparison of R-R-V and its significance to identify hazardous segments can be shown in Table 5.1. For convenience, the results are shown for the first 4.9 kilometre of Shibuya route 03-01 which consists of two on-ramps and one off-ramp. Two months (July and August) were taken in account to compare the results of number of crashes and system recovery rate. The focus of this comparison is to observe how the system reacts in two different situations: one with very high risk intensity (July) and another with very low risk intensity (August). Vulnerability of the system was then added to signify the comparisons.

Table 5.1 Significance of R-R-V Analysis

Detector Spacing (km)	July		August		Vulnerability of 6 months (mean = 14.1)
	Number of Crashes	Recovery Rate (mean = 0.15)	Number of Crashes	Recovery Rate (mean = 0.17)	
0.03	-	0.48	1	0.53	9.3
0.41	-	0.45	2	0.49	14.86
0.97	7	0.16	-	0.15	10.86
1.3	-	0.19	2	0.19	10.88
1.6	1	0.05	-	0.05	36.09
On-ramp 1					
1.9	-	0.04	3	0.04	17.52
2.2	-	0.04	-	0..04	10.93
2.4	2	0.05	-	0.06	12.90
2.71	1	0.02	1	0.02	18.35
3.12	1	0.05	-	0.03	8.09
Off-ramp 1					
3.8	-	0.05	-	0.05	22.23
On-ramp 2					
4.58	1	0.08	-	0.05	5.04
4.91	-	0.09	1	0.07	1.53

The possible causes of congestion and crashes which is discussed earlier can easily be verified from the results of R-R-V for the particular road segment. For a better understanding two months are considered. According to the reliability heat map, the risk intensity was very much higher in July than the other five months so the system showed lower average recovery rate and more number of crashes. In connectors, as the system was in congestion phase, it showed less crash occurrence as well as lower recovery rate due to the confluence. On the contrary, though the heat map suggested a higher intensity of reliability in August, few accidents have occurred due to over speeding, DUI and reckless driving. Low PRT due to over speeding and sudden lane change also had caused 3 crashes after On-ramp 1 converged to the freeway. From the overall analysis it can be justified that the system holds poor recovery rate when it faces a crash and falls into connector zones. Also the vulnerability of the system is much higher than the mean near on–ramp zones.

To improve the existing scenario several steps can be taken such as design modification of horizontal curvature, vehicle sight distance marker and traffic controlling and monitoring during peak hours. Using vulnerability prediction model risk zones can be easily detected. Special traffic signs and markers can be implied to warn the passengers for those vulnerable zones. Expressway performance evaluation may have impact on road network design and planning too.

5.3 Limitations and Recommendations

As no previous study exists on urban expressway performance evaluation this research work can be seen as a baseline. The work has considered only the inbound direction of Shibuya Route 03 expressway using the detector data of six months captured in 2014. Further assessment is required on different expressways with different variables to compare the new models with this study to improve the results and magnitudes of performance indicators.

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