CRITICAL INFRASTRUCTURE RENEWAL: A FRAMEWORK OF DYNAMIC MICROSIMULATION MODELLING FOR TRAFFIC IMPACT ASSESSMENT

by

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Dedicated to

My Father, Ali Abbas

My Mother, Arfa Begum

&

My Wife, Pauline Laila Bela

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Abstract

This thesis develops a dynamic microsimulation modelling framework for traffic impact assessment during the renewal of a critical infrastructure in Halifax transportation network. The complexity of the construction project poses considerable risks of disruption to the regular traffic operation. The uniqueness of this study is that it develops a sequential modelling framework combining risk assessment with traffic microsimulation. Furthermore, the existing practice of traffic microsimulation is improved by incorporating departure time (DT) choice model within microsimulation model. Two models were implemented; (1) a model without the DT component, and (2) a model with the DT component. The results of model 2 exhibit significant increase in traffic delays in the network. However, local traffic condition at key intersections improves if drivers' departure time adjustment is accounted within traffic microsimulation. Such inclusion of the DT model is of paramount importance for developing risk management strategies in the case of large-scale infrastructure project.

List of Abbreviations and Symbols Used

μ	Membership value
σ	Standard deviation
R^2	Goodness fit of the model
T	Travel time
π	Weighting factor
d	Departure time segment
α , β	Degree of diminishing sensitivity
λ	Degree of loss aversion
GEH	A modified chi-square statistic
LOS	Level of Service
DT	Departure time
DTA	Dynamic traffic assignment
PAT	Preferred arrival time
CI	Critical infrastructure
CPT	Cumulative prospect theory
TDM	Traffic demand management

Glossary

Transport network	Set of links, nodes that permits the traffic movement
Traffic microsimulation	Simulation of traffic flows at finer-grained level
VISSIM	A simulator to perform traffic microsimulation
Origin	Location where a trip starts
Destination	Location where a trip ends
Traffic assignment	Distribution of traffic on different paths between given origins and destinations in the network
DTA	Dynamic traffic assignment (DTA) that captures the spread of congestion over space and time in the transport network
Queue length	A collection of one or more than one vehicle on a link in the transport network that cannot move due to congestion or red signal
LOS	Level of Service (LOS) is a measure of the performance of the elements of the transportation infrastructures
DT	Departure time (DT) represents the instant of time that one needs to leave from home or work
PAT	Preferred arrival time (PAT) refers to the general work start time
CPT	Cumulative prospect theory (CPT), a behavioural economic theory that describes how people choose from probabilistic alternatives under risk
Loss aversion	Refers to people’s tendency to prefer not to lose rather than achieving gain

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Chapter 1

Introduction

1.1 Background and Motivation

Public Safety Canada defines Critical Infrastructures (CI) as the processes, systems, facilities, technologies, networks, assets and services essential to health, safety or economic well-being of the Canadians and effective functioning of government *(Public Safety Canada, 2014)*. According to *Quigley (2015)*, what constitutes 'critical' is deeply embedded in time, place, perspective and social context *(Boholm, 2012)*. Critical Infrastructures for instance, bridges are the vital links in a transport network. Any disruption to bridge operation affects the network significantly by completely shutting down a critical link. The renewal of a bridge is therefore a delicate process, particularly when the construction commences at night and the bridge is in use during the day. The MacDonald Bridge is a critical infrastructure in Halifax, Canada. This is one of the two major links used to travel between Halifax and Dartmouth. The MacDonald Bridge is currently going through a major re-decking project initiated by the Halifax Harbour Bridge Commission in October 2015, to replace the entire suspended spans of the bridge. This is the second time in history the suspension bridge is being replaced at night and in use during the day, the first being the Lions Gate Bridge in Vancouver. The complex construction procedures in this project make it vulnerable to possible disruption. Weather on the east coast of Canada also further contributes to increase the possibility of the disruption to the constructions. The disruption in night re-decking will delay the re-opening of the bridge in the morning resulting in significant traffic impacts on surrounding network. Moreover, the sudden closure of the MacDonald Bridge will make the other bridge a choke point during the morning rush hour. Understanding the traffic impact assessment is of paramount importance given the role this bridge plays in the network. Therefore, this study aims to offer a traffic impact assessment using a microscopic traffic simulation framework.

There are many traffic impact studies which analyzed the traffic and behavioral effects of bridge closure for a longer duration *(Hunt et al 2002; Zhu et al. 2011).* These studies adopted different modelling techniques including local and regional scale evaluation to analyze the impacts after the disruption to the bridge operation. However, analysis of immediate traffic impacts using microsimulation techniques on surrounding network due to sudden bridge closure is limited. The traffic impacts during the closure of the bridge can efficiently be evaluated within a traffic microsimulation platform. Microscopic traffic simulation has evolved over the last two decades in transportation operation and planning applications. Traffic microsimulation is capable of testing designed scenarios regarding the disruption on the transport network. The microsimulation-based approach could mimic the driver behavior at the finer-grained resolution during the sudden, unexpected interruptions in the transport network. Particularly, a dynamic traffic microsimulation efficiently captures the detailed driver's behaviour, including stochastic re-routing. The model offers micro-level network performance measures, for instance, delays, travel time, etc. Despite many advantages, existing traffic microsimulation models generally neglect traveller's departure time decision which is critical, especially during decision making under risk. Often, the travellers might depart from home late or early in response to sudden risk in the network. Hence, this study proposes a novel framework that integrates a departure time choice model within the dynamic traffic microsimulation modelling system to better estimate the traffic impacts on the network during an unscheduled closure of a critical infrastructure in Halifax, Canada.

1.2 General Objective

The main objective of the thesis is to develop a framework to assess the traffic impacts in the network resulting from the sudden closure of the MacDonald Bridge during the renewal project.

1.2.1 Specific Objectives

The specific research objectives are as follows:

1. To develop a microsimulation model that addresses risk scenarios and assess traffic impacts due to sudden disruptions
2. To examine a dynamic traffic assignment-based model to incorporate driver’s stochastic behaviour for a better estimates of the traffic impacts
3. To improve the dynamic traffic assignment (DTA)-based microsimulation by incorporating departure time choice model

1.3 Thesis Outline

The thesis consists of five main chapters. The second chapter describes how risk assessment informs the microsimulation modelling the scenario building process and presents the simulation results. The third chapter presents a DTA-based modelling approach to improve the microsimulation model for traffic impact assessment. The chapter offers a comprehensive traffic impact analysis during the closure of the MacDonald Bridge. Chapter four presents an attempt to accommodate a shortcoming of the DTA-based traffic microsimulation model which lacks a departure time choice component. The modelling framework presented in this chapter develops a departure time choice model for traffic microsimulation to capture the differential responses of the drivers towards a sudden closure of the bridge in the Halifax network. The final chapter, chapter five, summarizes key findings of the thesis and draws out the overall implications of the research.

Chapter 2

Risk Assessment and Microsimulation Modelling[1]

2.1 Introduction

Risk is inherent in large construction projects and causes potential complications in achieving the project goals. Risk could greatly plague a construction project, which necessitates risk assessment, particularly, for large scale construction projects. Risk assessment is critical for new construction or renewal of critical infrastructure (CI), such as bridges as they are the vital links for a transport network. Complexity in longer-duration road construction projects and constant exposure to environmental conditions increase the vulnerability of large CI construction projects to unexpected hazardous events. Literature offers a plenty of evidence of schedule slippage and thereby failures to attain the objectives of construction projects. Many factors such as weather, labor issues, and incidents are responsible for construction delays and cost overruns of construction projects *(Baldwin et al., 1984; Ayyub and Halder, 1984; Smith and Hancher, 1989).* Among many, the most weather- susceptible road construction activities might include earthwork, road paving, and structural work, including bridge re-decking and activities involving the use of heavy crane machinery *(Apipattanavis et al., 2010).* These risk factors and events have made the road construction delay a likely circumstance, often having significant impacts on project duration and traffic flows on surrounding road network. In many cases, the delay of road construction projects might not be avoided; however, the associated impacts on road network can be assessed and mitigated prior to commencing construction. Recently, Halifax Harbour Bridge (HHB) Commission has begun a re-decking project known as the

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[1] This chapter is adapted from:

Alam, M. J., Habib, M. A., and Quigley, K. "Critical Infrastructure Renewal: A Framework for Fuzzy Logic Based Risk Assessment and Microscopic Traffic Simulation Modelling". *In Journal of Transportation Research Procedia (in press),* 2016.

"Big Lift" in order to replace the suspended spans of the MacDonald Bridge, a 1.3 km long CI in Halifax, Canada. After the Lions' Gate Bridge re-decking in Vancouver (2000-2001), this is the second time in history a suspension bridge is being replaced while maintaining traffic during day-time. The project will last for almost 18 months. The associated risk of disruption to the projects and potential traffic impacts could be significant as up to 48,000 vehicles, 700 cyclists, and 750 pedestrians cross the bridge every day, yet the consequences of disruption to the MacDonald Bridge have never been studied *(Quigley, 2015).*

Therefore, this chapter presents a fuzzy logic-based approach to assess risk scenarios resulting in unscheduled closure of the bridge, and develops a microsimulation model to assess the traffic impacts due to bridge opening delays during the "Big Lift" project. The re-decking started in October, 2015. Construction commences at 7:00 pm, with the bridge becoming operational again at 5:30 am the following morning. The main objectives of this study is (a) to develop a risk assessment framework to estimate the construction related bridge opening delay in the morning, and (ii) to assess the traffic impacts due to bridge opening delay utilizing a microsimulation model. The risk analysis feeds the simulation process with possible delay scenarios in the AM peak period. The impacts are evaluated based on specific Measures of Effectiveness (MOEs) such as average queue length, average travel time, average delay, average speed, and traffic flow indicators.

2.2 Literature Review

Construction is susceptible to various risks such as construction phase related risk, weather, political and contract provision, finance, environmental, and design related risks. Schedule slippage is inherently embedded into construction projects as a result of potentially unforeseen events. A survey, conducted for forty US construction managers and owners revealed that at the beginning of the project, only 35% of the assessed projects had been found to have a low uncertainty. This means that the remaining 65% of the projects had a medium to very high uncertainty *(Laufer et al., 1992).* Literature review suggests that sometimes teams of experienced engineers and practitioners are unable to anticipate this uncertainty. Therefore, risk assessment plays a vital role in construction management. Many studies have investigated project risks, activity scheduling, and construction delays, risk factors and risk management methods. For example, *Kaliba et al. (2009)* identified heavy rain and delay in labor payment are main causes responsible for the cost escalation and schedule delay in road construction. However, a majority of these studies have focused on small-scale construction and routine roadway management. As indicated earlier, risk assessment is critical for CI construction projects; several researchers have conducted risk assessment studies for CI development projects, including bridges and nuclear power plants *(Nieto Morote and Ruz-Vila, 2011; Wang and Elhag, 2007; Farughi and Heshami, 2011)*. Most recent studies primarily involve structural risk assessment to prioritize bridge repair and maintenance projects. Although studies of structural health monitoring and structural risk analysis of CI are numerous, only few involved the study of the construction delay risk of CI or major transportation investment projects. For example, *Hossen, et al. (2015)*, used Analytical Hierarchy Process (AHP) and Relative Importance Index (RI) for assessing the schedule delay risk for the construction of a nuclear power plant. However, as the Critical Infrastructures, including bridges, are vital links in road networks, an appropriate risk assessment method should be in place to avoid any operational discontinuity of CI due to the construction delays as well as to limit the cost overruns of the project. In this context, the collapse of the I-35 Bridge can be a good example to illustrate the consequences in relation to the operational discontinuity of the bridge. The collapse of I-35 Bridge resulted in an economic loss to road users of US$71,000 to US$220,000 per day *(Xie and Levinson, 2011)*. Therefore, it is important to assess the risk potential in CI renewal and their associated impacts on traffic flows, which could offer significant insights for cost assessment and mitigation strategies.

Since the re-decking of the suspension bridge in Halifax will occur at night-time, and open in the morning, risk mitigation is of paramount importance. There is potential for construction delay each day as complex engineering manoevring is involved each night. Weather and local environmental condition of the Canadian East Coast could also be challenging factors in terms of timely completion of the scheduled activities. Therefore, this study has investigated the construction related bridge opening delay and assessed the associated impacts on the surrounding transport network. As indicated earlier, different types of techniques are used for risk assessment for small scale construction such as AHP, RI. Few other techniques include Critical Path Method (CPM), Program Evaluation and Review Technique (PERT), Graphical Evaluation and Review Technique (GERT). These methods are either deterministic or probabilistic. In addition, sometimes some parameters cannot be quantified either due to data unavailability or the nature of factors considered for risk assessment. On the other hand, sometimes consequences of risks can only be described subjectively, for instance, in terms of linguistic terms only. Literature suggests that the fuzzy logic-based approach is effective in quantifying these subjective judgments. This method can be advantageous in establishing the relationships among the risk sources, risk events, and the consequences. It has been found that fuzzy logic is used in the field of project scheduling, activity delay analysis, and daily schedule updating and monitoring because of its superiority in incorporating qualitative factors in the estimation of the risk parameters *(Oliveros et al., 2005; Ayyub and Halder, 1984; Smith and Hancher, 1989).* Moreover, a fuzzy based decision making model is capable of handling the experts' knowledge, imprecise historical data, and engineering judgment in construction project risk management *(Zeng et al., 2007). Chun and Ahn (1992)* also demonstrated the use of the fuzzy logic for quantifying the imprecision in human reasoning and judgmental uncertainties of accident progression event trees. There is numerous application of fuzzy logic techniques in bridge risk assessment and other construction projects *(Wang and Taha, 2007; Carr and Tah, 2001; Cho et al., 2002; Kuchta, 2001).* Most of them focuses on the structural performance to prioritize the repair works and determining the overall project delay duration. This study extends the fuzzy logic technique for risk assessment, particularly to estimate the bridge opening delay on a given day due to the interruption to night re-decking during the Big Lift project.

The study evaluates the effects of key weather related parameters including wind, temperature, and precipitation within a fuzzy logic-based risk assessment framework. In addition, potential bridge construction incidents are also considered for risk assessment. The delay assessment informs the scenario building process for the traffic impact assessment within a microsimulation platform.

Microscopic traffic simulation has evolved as a very powerful tool in transportation engineering for traffic impact assessment. There is a growing interest in using microsimulation techniques in construction projects. *Holman (2012)* examined different deck replacement methods, and found that the travel time increases from 94.26 sec at 500 vehicles/hour to 97.93 sec at 2200 vehicles/hour for free flow scenario and from 115.79 sec to 119.82 sec for reduced speed scenario during deck replacement. Lane or bridge closure is a very common phenomenon in a work zone or an emergency period, which might exert severe impacts on traffic. Microsimulation techniques could better mimic the traffic flow within the transport network, and offer finer-grained speed trajectories, queue and delay measures. Many traffic microsimulation studies exist that assessed the impacts of before, after, and during construction. For instance, *Watt et al. (2012)* evaluated a single lane closure event during construction of freeway using microsimulation model. Furthermore, daily effect of roadway maintenance and disrupted traffic were also evaluated using microsimulation models *(Huang et al., 2009)*. Recently, a microsimulation study on Montreal's Champlain Bridge closure, reports that lane closure will expand the intensity and length of the peak periods, and could cost the city up to $1.4 million loss in economic output *(Ferguson, 2011)*.

Given that the MacDonald Bridge is a critical infrastructure, it is necessary to evaluate traffic impacts at a finer-grained spatial and temporal resolution. The bridge not only connects twin cities, Halifax and Dartmouth, but also acts as a vital link to the port of Halifax and rest of Canada. This study takes a microscopic network modelling approach. The uniqueness of this study is that it develops a sequential modelling framework that combines risk assessment with microsimulation modelling. Particularly, the assessment on the construction delay informs the scenario building process for the traffic model. Possible case scenarios are developed based on the fuzzy-based delay analysis. Risk assessment and traffic microsimulation methods are briefly discussed below.

2.3 Methodology

2.3.1 Basic Concepts of Fuzzy Set Theory

Fuzzy sets were first introduced by *Zadeh (1965)* as a way of dealing with imprecision or uncertainty with data in risk assessment problems. They are the generalizations of crisp sets. A fuzzy set is a collection of elements in a universe of information where the boundary of the set contained in the universe is ambiguous, vague, and otherwise fuzzy. Each fuzzy set can be defined by a membership function and this function assign a value within the interval [0, 1] to each element contained in the universe of discourse. The assigned value represents the degree of the membership or grade of a given element to the fuzzy set. A value of '0' means no membership and a value of '1' implicates a full membership to the set. The value in between 0 and 1 indicates a partial membership of an element to the fuzzy set. Thereby, a fuzzy set can be uniquely specified by its membership function.

Let A be a subset of discourse X, a set of elements x_i. Each element, x can be assigned a membership value, $\mu_A(x)$ obtained from the membership function on X. There are two distinct natures of the set A: (i) A can be non-fuzzy, crisp set, (ii) Otherwise fuzzy. If A is a non -fuzzy set, then the membership function can be defined as below:

$$\mu_A(x) = \begin{cases} 0, \textit{if x does not belong to A} \\ 1, \textit{if x does belong to A} \end{cases} \tag{1}$$

According to equation 1, set A follows strict boundaries which are '0' and '1', offers two options for an element, either it belongs to A, $\mu_A(x)$ =1, or does not, $\mu_A(x)$ = 0. On the other hand, if set A is a fuzzy set, the membership function is free to take any value within the interval [0, 1]. Therefore, the degree of membership varies from no membership to full membership of an element to the set A, it doesn't hold any sharp boundaries. The following Figure 2-1 illustrates crisp and fuzzy sets.

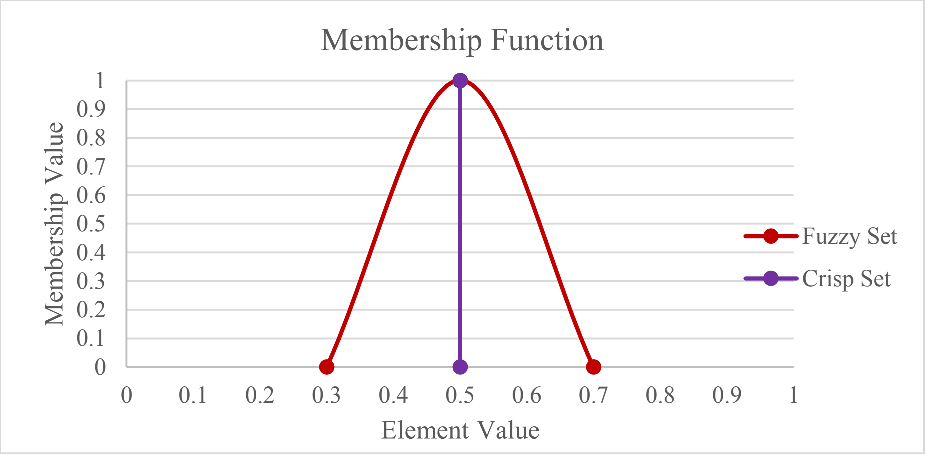


Figure 2-1 A Fuzzy Membership Function

Input membership function can be of different forms, including triangular, trapezoidal, gaussian, bell-shape, and others. For the simplicity in formulation and computation, the triangular and trapezoidal membership functions are extensively used in real life implementation. This study used the triangular membership function as below:

$$\mu_A(x) = \begin{cases} (x-a)/(b-a), & a \le x \le b \\ (d-x)/(d-b), & b \le x \le d \\ 0, & otherwise \end{cases} \tag{2}$$

2.3.2 Simple Operation of Fuzzy Logic

2.3.2.1 Fuzzy Union

The union, U of two fuzzy subsets (i.e. A and B) of a universe refers to the connective 'or' and can be defined as below:

$$\mu_{A\cup B}(x) = max[\mu_A(x), \mu_B(x)] \tag{3}$$

Where,

$\mu_{A\cup B}(x)$ = membership value of x in fuzzy set $A \cup B$

$\mu_A(x)$ = membership value of x in fuzzy set A

$\mu_B(x)$ = membership value of x in fuzzy set B

2.3.2.2 Fuzzy Intersection

The intersection, $\cap$ of two fuzzy subsets (i.e. A and B) of a universe refers to the connective 'and' and can be defined as below:

$$\mu_{A\cap B}(x)=min[\mu_A(x),\mu_B(x)] \tag{4}$$

Where,

$\mu_{A\cap B}(x)$ = membership value of x in fuzzy set $A\cup B$

$\mu_A(x)$ = membership value of x in fuzzy set A

$\mu_B(x)$ = membership value of x in fuzzy set B

2.3.2.3 Fuzzy Relation

Fuzzy relation refers to the combining of two fuzzy subsets that belong to different universes. Fuzzy relations are specified in the form of conditions for example, if the labors are efficient, the delay in construction will be minimum. Mathematically, if A is a fuzzy subset in the universe, X and B is a fuzzy subset in the universe, Y, then a fuzzy relation $R\ (M,\ N)$ refers to a Cartesian product, $M\times N$, between the fuzzy subset, M, and fuzzy subset, N. The membership values of the elements of $R\ (M,\ N)$ are computed as below:

$$\mu_R(x_m,y_n)=min[\mu_M(x_m),\mu_N(y_n)] \tag{5}$$

Where.

$\mu_R(x_m,y_n)$ = membership value of element, (x_m,y_n) in fuzzy relation matrix $R\ (M,\ N)$

$\mu_M(x_m)$ = membership value of element, x_m in fuzzy relation matrix M

$\mu_N(x_n)$ = membership value of element, x_n in fuzzy relation matrix N

x_m and y_n are the elements of universe X and Y respectively

2.3.2.4 Union of Fuzzy Relation

Fuzzy logic model is capable of joining more than one fuzzy relations into a union matrix according to following equation 6.

$$\begin{aligned} T &= (M_1 \times N_1) \cup (M_2 \times N_2) \cup (M_3 \times N_3) \ldots\ldots\ldots\ldots\ldots\ldots \\ T &= max[(M_1 \times N_1),(M_2 \times N_2),(M_3 \times N_3) \ldots\ldots\ldots\ldots] \end{aligned} \tag{6}$$

Where, T is a union matrix of all fuzzy relations $R\ (M,\ N)$ and the relations are from universe X to universe Y.

2.3.2.5 Fuzzy Composition

If T is a fuzzy relation X to Y, and S is a fuzzy relation from Y to Z, then fuzzy model performs the composition of T and S using the max-min composition method as below.

$$\mu_{ToS}\ (x_m, z_o) = \underset{y_n}{max}[min\ [\mu_T\ (x_m, y_n), \mu_S\ (y_n, z_o)] \tag{7}$$

Where

$\mu_{ToS}\ (x_m, z_o)$ = membership value of element, (x_m, z_o) in fuzzy composition matrix ToS

$\mu_T\ (x_m, y_n)$ = membership value of element, (x_m, y_n) in union matrix T

$\mu_s\ (y_n, z_o)$ = membership value of element, (y_n, z_o) in union matrix S

x_m, y_n and z_o are the elements of universe X, Y, and Z respectively

2.3.3 Fuzzy-based Delay Estimation

Imprecision in information for decision making and uncertainty creates mammoth challenges in completing construction projects on time. According to *Ridwan (2004)*, conventional crisp choice models are less capable of handling this type of uncertainty and vagueness in decision making. Fuzzy logic method makes it possible to quantify subjective judgments and incorporate the imprecision in human reasoning and thereby, improve the decision making. Cable Bridge re-decking, such as the MacDonald Bridge renewal is an occasional construction project. Night-time construction and day time use of the bridge make the construction activities more sensitive to a variety of risks. Insufficient information and lack of experiential knowledge of the impact of this type of project along with uncertain maritime weather factors adds further uncertainty in risk assessment. The risks and associated consequences for this kind of rare project is susceptible to a degree of truth rather than referring directly to the either 'True' or 'False'. Fuzzy logic technique deals with this type of partial truth in risk modelling. Therefore, this study adopted the fuzzy logic technique applied in construction scheduling by *Ayyub and Halder (1984)* and *Smith and Hancher (1989)*. The construction of the MacDonald Bridge is scheduled at night and involves the lifting of the deck slab with a lifting gantry. This study assumes two categories of risk factors including weather-related factors and unexpected bridge construction incidents that could affect the opening hours of the bridge in the morning. Identification of risk involves several steps. First, this study identifies the factors and thresholds (see Appendix A1) that pose risks based on the literature and engineering judgment. According to *Halifax Harbour Bridge Commission (2015)*, wind speed (km/hr.) could be a challenging factor during night re-decking. The other factors include temperature (^{o} C), precipitation (mm), and bridge construction incident. Precipitation adds up the rainfall and the water equivalent of the snowfall in millimeters. Weather data is obtained from the Environment Canada *(Canadian Weather, 2015)* for Fall season, 2014. Fall season prevails from mid-September to mid-December in Halifax. December is the transition month from Fall to Winter. December is found to have relatively a volatile weather condition in terms of wind speed, reflects at wider standard deviation (see Appendix A1). Additionally, traffic movement during the holiday season increases the possibility of the disruptions to the network. Therefore, this study selected December for empirical testing. Then, it determines the frequency of occurrences of the identified factors. Afterwards, the consequences of different factors on re-decking activity is subjectively categorized into three levels: Low, Medium, and High as identified in Table 2-1. This process demonstrates the appropriateness of taking a fuzzy-based approach as identification of the factors and attributes (e.g., frequency of occurrences, consequences on re-decking) can be best described in linguistic terms.

The frequency of occurrence for each state of factors (alternatively referred as parameters) are determined based on the observed weather data and translated into linguistic terms (e.g., Low, Medium, and High). The bridge construction incident is also categorized as Low impact, Medium impact, and High impact incidents based on engineering judgments. All cases considered in this study are presented in Table 2-1.

Table 2-1 Factors, Frequency of Occurrence, and Consequence Types

Factors		Frequency of Occurrence	Case 1	Case 2	Case 3
			Low consequence	Medium consequence	High consequence
Wind (km/hr)	Low	High	Low	Medium	High
	Medium	Medium	Low	Medium	High
	High	Low	Low	Medium	High
Temperature (^{o} Celsius)	Low	Low	Low	Medium	High
	Medium	Medium	Low	Medium	High
	High	Low	Low	Medium	High
Precipitation (mm)	Low	High	Low	Medium	High
	Medium	Medium	Low	Medium	High
	High	Low	Low	Medium	High
Bridge construction incident	Low	Medium	Low	Medium	High
	Medium	Low	Low	Medium	High
	High	Low	Low	Medium	High

Next, each linguistic term of each attribute state of frequency of occurrence and consequences is translated into fuzzy sets by assigning the membership value within the interval [0, 1] for each element from 0 to 1 that defines the linguistic term. The grade of the membership represents the confidence that the member belongs to the fuzzy set; larger values (closer to 1) denote higher degrees of membership. This study adopts expert's opinion and engineering judgments in assignment of the membership values. The membership values of frequency of occurrences and consequences are shown in Table 2-2.

Table 2-2 Membership Function of Frequency of Occurrence and Consequences

Elements of linguistic variables	Membership values for frequency of occurrence											
	Wind			Temperature			Precipitation			Construction Incidents		
	Low	Medium	High	Low	Medium	High	Low	Medium	High	Low	Medium	High
0.0	1.00	0.00	0.00	1.00	0.00	0.00	1.00	0.00	0.00	1.00	0.00	0.00
0.1	1.00	0.00	0.00	1.00	0.57	0.00	1.00	0.00	0.00	1.00	0.00	0.00
0.2	1.00	0.00	0.00	0.00	0.96	0.00	1.00	0.00	0.00	1.00	0.00	0.00
0.3	1.00	0.00	0.00	0.00	0.81	0.19	1.00	0.00	0.00	1.00	0.00	0.00
0.4	0.84	0.16	0.00	0.00	0.67	0.33	0.83	0.17	0.00	0.78	0.22	0.00
0.5	0.69	0.31	0.00	0.00	0.52	0.48	0.67	0.33	0.00	0.56	0.44	0.00
0.6	0.53	0.47	0.00	0.00	0.37	0.63	0.50	0.50	0.00	0.33	0.67	0.00
0.7	0.38	0.63	0.00	0.00	0.22	0.78	0.33	0.67	0.00	0.11	0.89	0.00
0.8	0.22	0.78	0.00	0.00	0.07	0.93	0.17	0.83	0.00	0.00	0.75	0.25
0.9	0.00	0.94	0.00	0.00	0.00	1.00	0.00	1.00	0.00	0.00	0.25	0.75
1.0	0.00	0.00	1.00	0.00	0.00	1.00	0.00	0.00	1.00	0.00	0.00	1.00

Elements of linguistic variables	Membership values for consequences		
	Low	Medium	High
0.0	1.00	0.00	0.00
0.1	1.00	0.00	0.00
0.2	0.71	0.29	0.00
0.3	0.43	0.57	0.00
0.4	0.14	0.86	0.00
0.5	0.00	0.88	0.00
0.6	0.00	0.63	0.00
0.7	0.00	0.38	0.00
0.8	0.00	0.13	0.70
0.9	0.00	0.00	1.00
1.0	0.00	0.00	1.00

Next step is the formation of the fuzzy relation matrix followed by the probability estimation of the delay duration. Detailed steps are shown for case 1 for illustration purpose only. The same procedure applies to case 2 and case 3. First, fuzzy relation matrix, $M\,(F, C)$ is created to combine the fuzzy subsets of frequency of occurrences F and fuzzy subsets of consequences, C. The calculation refers to a Cartesian product $(F \times C)$ and the relation can be formulated according to the equation 5 (see section 2.3.2.3).

In total 12 fuzzy relation matrices are obtained for case 1, since each of the four factors (i.e., wind, temperature, precipitation, and bridge construction incident) is described by three attribute states (low, medium, and high). Two example matrices are shown in Table 2-3. All other $M(F,C)$ relation matrices are shown in Appendix A2. Afterwards, 12 matrices are combined into a total matrix, T (see in Table 2-6a) based on the equation 6 (see section 2.3.2.4).

Table 2-3 Fuzzy Relation Matrices of Frequency of Occurrence and Consequence

Wind							Temperature						
Consequences=Low							Consequences=Low						
		0	0.1	0.2	0.3	0.4			0	0.1	0.2	0.3	0.4
Frequency of Occurrence= Low	0.0	1.0	1.0	0.71	0.43	0.14	Frequency of Occurrence= Medium	0.0	0.00	0.00	0.00	0.00	0.00
	0.1	1.00	1.00	0.71	0.43	0.14		0.1	0.96	0.96	0.71	0.43	0.14
	0.2	1.00	1.00	0.71	0.43	0.14		0.2	0.81	0.81	0.71	0.43	0.14
	0.3	1.00	1.00	0.71	0.43	0.14		0.3	0.67	0.67	0.67	0.43	0.14
	0.4	0.84	0.84	0.71	0.43	0.14		0.4	0.52	0.52	0.52	0.43	0.14
	0.5	0.69	0.69	0.69	0.43	0.14		0.5	0.37	0.37	0.37	0.37	0.14
	0.6	0.53	0.53	0.53	0.43	0.14		0.6	0.22	0.22	0.22	0.22	0.14
	0.7	0.38	0.38	0.38	0.38	0.14		0.7	0.07	0.07	0.07	0.07	0.07
	0.8	0.22	0.22	0.22	0.22	0.14		0.8	0.22	0.22	0.22	0.22	0.14

Subsequently, fuzzy relation matrix $N(C,D)$ is developed by combining the fuzzy subsets of consequences, C and fuzzy subsets of construction related bridge opening delay duration, D. The $N(C,D)$ matrices are obtained based on corresponding fuzzy relation between the consequences and the delay in bridge opening which can be described as (i) if the consequence is Low, then delay is Low, (iii) if the consequence is Medium, then delay is Medium and (iv) if the consequence is High, then delay is High. Table 2-4 presents the membership functions representing the delay duration and Table 2-5 presents an example of the $N(C,D)$ matrices. All other $N(C,D)$ matrices are shown in Appendix A3.

Next, all relation matrices $N(C,D)$ are combined into a union S according to a similar equation for T and the union S is illustrated in Table 2-6b.

Finally, a composition matrix ToS as shown in Table 2-6c is developed according to the equation 7 (see section 2.3.2.5).

Table 2-4 Membership Values for Delay Duration in Bridge Opening

Delay hours	Membership functions for delay duration in bridge opening		
	Low	Medium	High
0.0	1	0.0	0.0
0.5	0.8	0.0	0.0
1.0	0.4	0.6	0.0
1.5	0.0	1.0	0.0
2.0	0.0	0.5	0.5
2.5	0.0	0.0	1.0
3.0	0.0	0.0	1.0

Table 2-5 Fuzzy Relation Matrix of Consequences and Delay Elements

		Delay duration=Low		
		0	0.5	1
Consequence = Low	0.0	1.0	0.8	0.4
	0.1	1.0	0.8	0.4
	0.2	0.71	0.71	0.4
	0.3	0.43	0.43	0.40
	0.4	0.14	0.14	0.14

Table 2-6 (a) Union matrix, T, (b) Union matrix, S, and (c) Composition matrix, ToS

(a) Union matrix, T

		Consequence										
		0.0	**0.1**	**0.2**	**0.3**	**0.4**	**0.5**	**0.6**	**0.7**	**0.8**	**0.9**	**1.0**
Frequency of occurrence	**0.0**	1	1	0.71	0.43	0.14	0	0	0	0	0	0
	0.1	1	1	0.71	0.43	0.14	0	0	0	0	0	0
	0.2	1	1	0.71	0.43	0.14	0	0	0	0	0	0
	0.3	1	1	0.71	0.43	0.14	0	0	0	0	0	0
	0.4	0.84	0.84	0.71	0.43	0.14	0	0	0	0	0	0
	0.5	0.69	0.69	0.69	0.43	0.14	0	0	0	0	0	0
	0.6	0.67	0.67	0.63	0.43	0.14	0	0	0	0	0	0
	0.7	0.89	0.89	0.71	0.43	0.14	0	0	0	0	0	0
	0.8	0.93	0.93	0.71	0.43	0.14	0	0	0	0	0	0
	0.9	1	1	0.71	0.43	0.14	0	0	0	0	0	0
	1.0	1	1	0.71	0.43	0.14	0	0	0	0	0	0

(b) Union matrix, S

		Delay duration						
		0.0	**0.5**	**1.0**	**1.5**	**2**	**2.5**	**3**
Consequences	**0.0**	0	0.8	0.4	0	0	0	0
	0.1	1	0.8	0.4	0	0	0	0
	0.2	0.71	0.71	0.4	0	0	0	0
	0.3	0.57	0.57	0.4	0	0	0	0
	0.4	0.86	0.8	0.4	0	0	0	0
	0.5	0.88	0.8	0.4	0	0	0	0
	0.6	0.63	0.63	0.4	0	0	0	0
	0.7	0.38	0.38	0.38	0	0	0	0
	0.8	0.67	0.67	0.4	0	0	0	0
	0.9	1	0.8	0.4	0	0	0	0
	1.0	1	0.8	0.4	0	0	0	0

(c) Composition matrix, ToS

		Delay duration							Row summation	Frequecy product
		0.0	**0.5**	**1.0**	**1.5**	**2**	**2.5**	**3**		
Frequency of occurrences	**0.0**	1	0.8	0.4	0	0	0	0	2.2	0.0
	0.1	1	0.8	0.4	0	0	0	0	2.2	0.2
	0.2	1	0.8	0.4	0	0	0	0	2.2	0.4
	0.3	1	0.8	0.4	0	0	0	0	2.2	0.7
	0.4	0.84	0.84	0.4	0	0	0	0	2.08	0.8
	0.5	0.69	0.69	0.4	0	0	0	0	1.78	0.9
	0.6	0.67	0.67	0.4	0	0	0	0	1.74	1.0
	0.7	0.89	0.8	0.38	0	0	0	0	2.07	1.4
	0.8	0.93	0.8	0.4	0	0	0	0	2.13	1.7
	0.9	1	0.8	0.4	0	0	0	0	2.2	2.0
	1.0	1	0.8	0.4	0	0	0	0	2.2	2.2

The final composition matrix ToS is shown in Table 2-6c. Once the composition matrix is created, the maximization technique can be used proposed by *Ayyub and Haldar (1984)* to select a fuzzy subset of the composition matrix ToS in order to estimate the probability of the delay elements. The subset that maximizes the product of the row summation and frequency of occurrence is the desired subset to estimate the delay duration. This study found that the last row shown in Table 2-6(c) satisfies the condition. At the end, probability of delay duration, mean delay, and standard deviation can be obtained by:

$$P(D = z_o) = \frac{\mu_V(z_o)}{\sum_{o=1}^{k} \mu_V(z_o)} \tag{8}$$

$$Average\ Delay = \sum_{o=1}^{k} P(D = z_o) \times (z_o) \tag{9}$$

$$\sigma = \sqrt{\sum_{i=1}^{n} P(D = z_o) \times (z_o)^2 - D_{avg}{}^2} \tag{10}$$

Where, D = delay duration, z_o = element of the delay duration, $P(D = z_o)$ = probability of occurrence of the delay duration to be element, $\mu_V(z_o)$ =membership value of the element z_o in subset *V*, σ = standard deviation, and *k* = number of delay duration elements. Note that the element refers to 'hours' of delay in bridge opening. Table 2-7 shows the membership values of the desired subset, *V* for the corresponding delay hours.

Table 2-7 Fuzzy Subset (V) Obtained from the Composition Matrix

Delay hours	0.0	0.5	1.0	1.5	2.0	2.5	3.0
Membership values	1	0.8	0.4	0	0	0	0

Using Table 2-7 and equation 8, 9, and 10, delay probabilities at half an hour interval, average delay, and standard deviation can be estimated as follows:

0-hour delay: P (D=0) = 1/ (1+0.8+0.4) = 46%

0.5-hour delay: P (D=0.5) = 0.8/ (1+0.8+0.4) = 36%

1-hour delay: P (D=1) = 0.4/ (1+0.8+0.4) = 18%

Average Delay: 0.46*0 + 0.36*0.5 + 0.18*1 = 0.36 hour = 21.6 minutes ~ 22 minutes

Standard Deviation = $(0.46*0^2 + 0.36*0.5^2 + 0.18*1^2 – (0.36)^2)^{1/2}$ = 0.37 hour

This study reveals that the average delays could be 22 minutes, 1.5 hours, and 2.6 hours for low, medium, and high consequences respectively. Table 2-8 shows the probability estimation for all the cases. The results suggest that the probability of delay in bridge opening for low consequence on activity duration ranges from 18%-36% while 25%-45% is for medium consequence. Interestingly, 2.5, and 3-hour delay is equally probable for the high level of consequence. The values of the standard deviation suggest that the delay results for medium consequence are more reliably predictable compared to low and high consequences.

Table 2-8 Delay Probabilities in Bridge Opening

Cases	0-hr. delay	0.5-hr. delay	1.0-hr. delay	1.5-hr. delay	2.0-hr. delay	2.5-hr. delay	3.0-hr. delay	Avg. delay (hour)	Standard deviation (hour)
Low consequence	46%	36%	18%	_	_	_	_	0.36	0.37
Medium consequence	_	_	30%	45%	25%	_	_	1.5	0.25
High consequence	_	_	_	_	20%	40%	40%	2.6	0.37

Given that bridge opening delay is found to be ranging from 0.5 hour to 3 hours, this study selects multiple scenarios to evaluate traffic impacts. An hourly interval of delay scenario is preferred for parsimony and consistent evaluation of Measures of Effectiveness (MOEs).

2.3.4 Microsimulation Modelling-based Approach

2.3.4.1 Traffic Simulation Platform

This study uses PTV VISSIM 6.0 to develop a microsimulation-based traffic model for Halifax network. The name **VISSIM** is derived from German **Verkehr In Städten - SIMulationsmodell** which stands for **Traffic in cities - simulation model**. This is a microscopic traffic simulator that is capable of analyzing and optimizing traffic flows. This commercial traffic simulator is gaining interests among engineers, planners and practitioners. It can model the psycho-physical driving behaviour both on the urban network and freeway section of the road. It can implement both interrupted and uninterrupted traffic scenario regardless of the geometry of the road network. Complex traffic condition can be visualized and analyzed at finer-grained detail in this platform.

2.3.4.2 Study Area

Figure 2-2 shows the study area considered in simulation. The area includes Halifax and Dartmouth linked by the two Critical Infrastructure (CI), the MacDonald and the Mackay Bridge. The area is almost 4 km in width and 6 km in length.

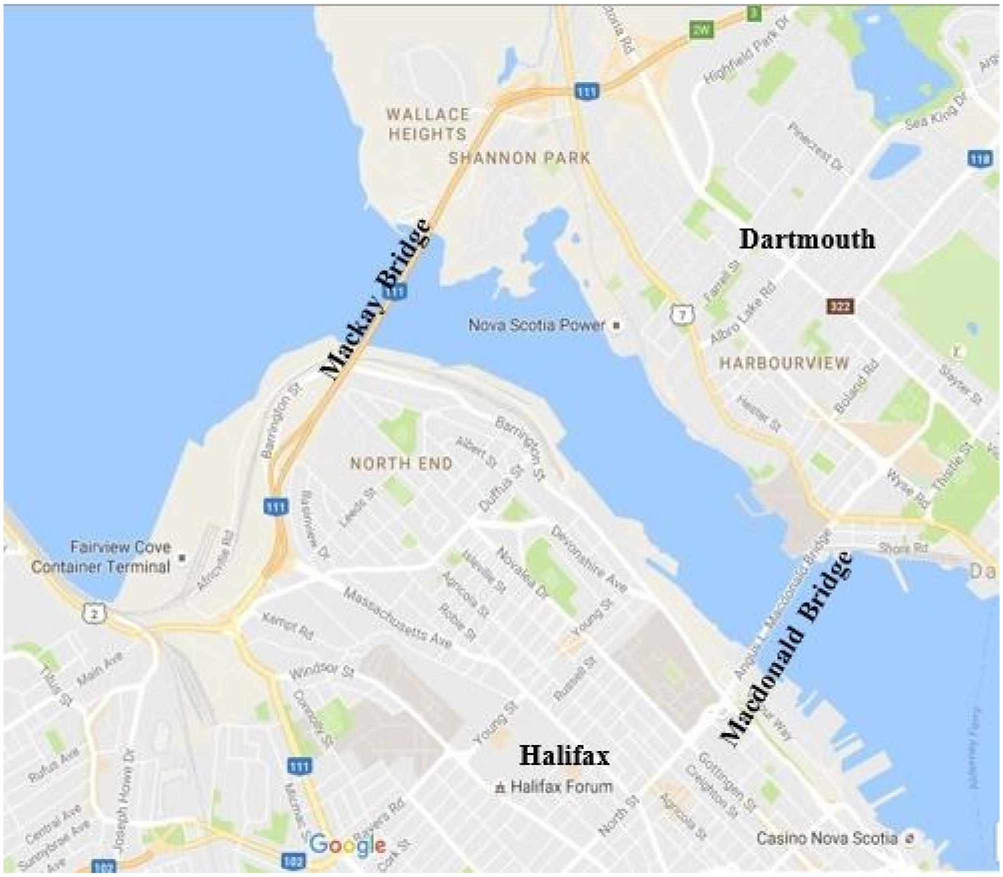


Figure 2-2 An Illustration of Study Area

2.3.4.3 Data Sources

Road Data

Halifax Regional Municipality (HRM) street file is used to identify the true geometry and locations of different network elements during network coding in VISSIM. Verification is performed by Google Earth. Necessary geometry information including number of links and lanes, grade, direction and turning restrictions have been derived from the Google Map Street View, Halifax Geodatabase, 2012, and field visits.

Traffic Count and Signal Data

Directional traffic count and signal timing has been obtained from the Public Work Traffic Study of Halifax Regional Municipality (HRM), 2014. All of the controlled traffic signals within the study area were pre-timed. Signal cycle length, phase split was included in the obtained data and were used to model the signal in the simulation model. The following Figure 2-3 and Figure 2-4 show the traffic count data and signal data used for microsimulation modelling. Figure 2-5 illustrates a signal controller coded in VISSIM.

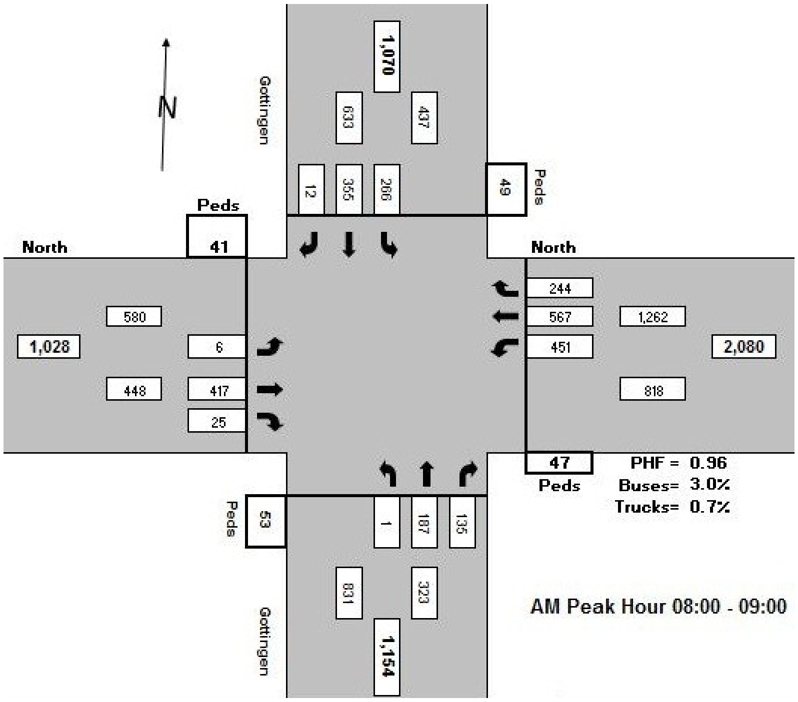
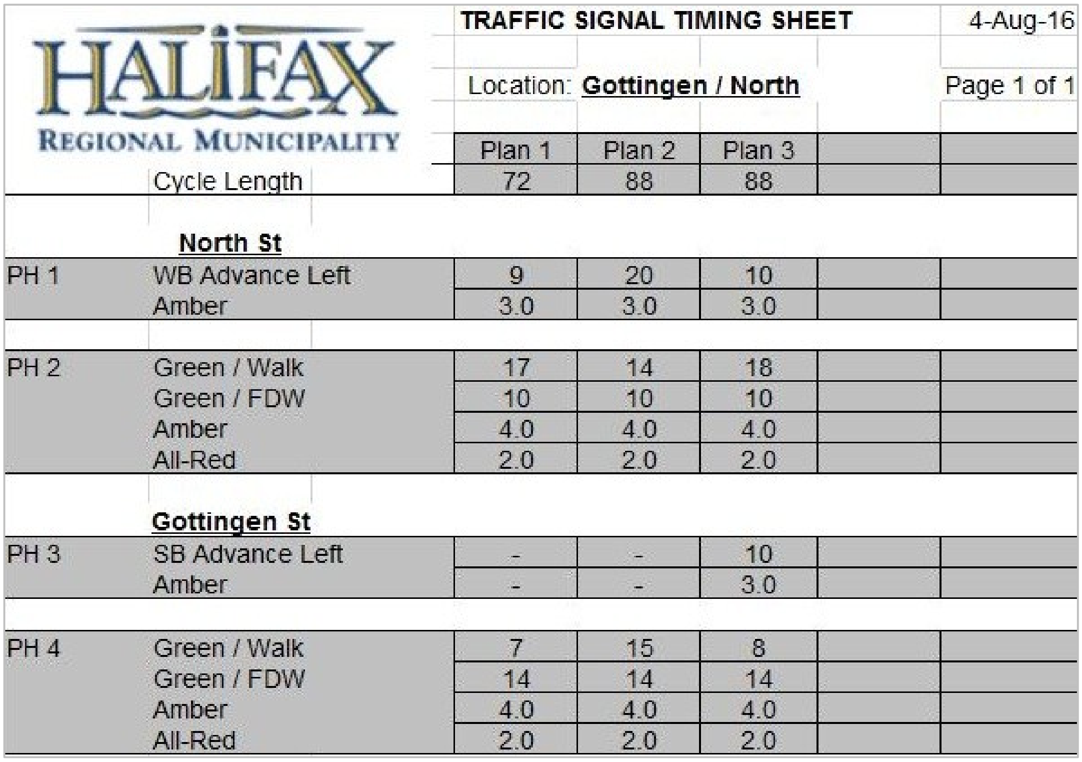


Figure 2-3 Traffic Count Data Sheet Format



HALIFAX REGIONAL MUNICIPALITY

TRAFFIC SIGNAL TIMING SHEET 4-Aug-16

Location: **Gottingen / North** Page 1 of 1

		Plan 1	Plan 2	Plan 3		
	Cycle Length	72	88	88		
	North St					
PH 1	WB Advance Left	9	20	10		
	Amber	3.0	3.0	3.0		
PH 2	Green / Walk	17	14	18		
	Green / FDW	10	10	10		
	Amber	4.0	4.0	4.0		
	All-Red	2.0	2.0	2.0		
	Gottingen St					
PH 3	SB Advance Left	-	-	10		
	Amber	-	-	3.0		
PH 4	Green / Walk	7	15	8		
	Green / FDW	14	14	14		
	Amber	4.0	4.0	4.0		
	All-Red	2.0	2.0	2.0		

Figure 2-4 Signal Data Sheet Format

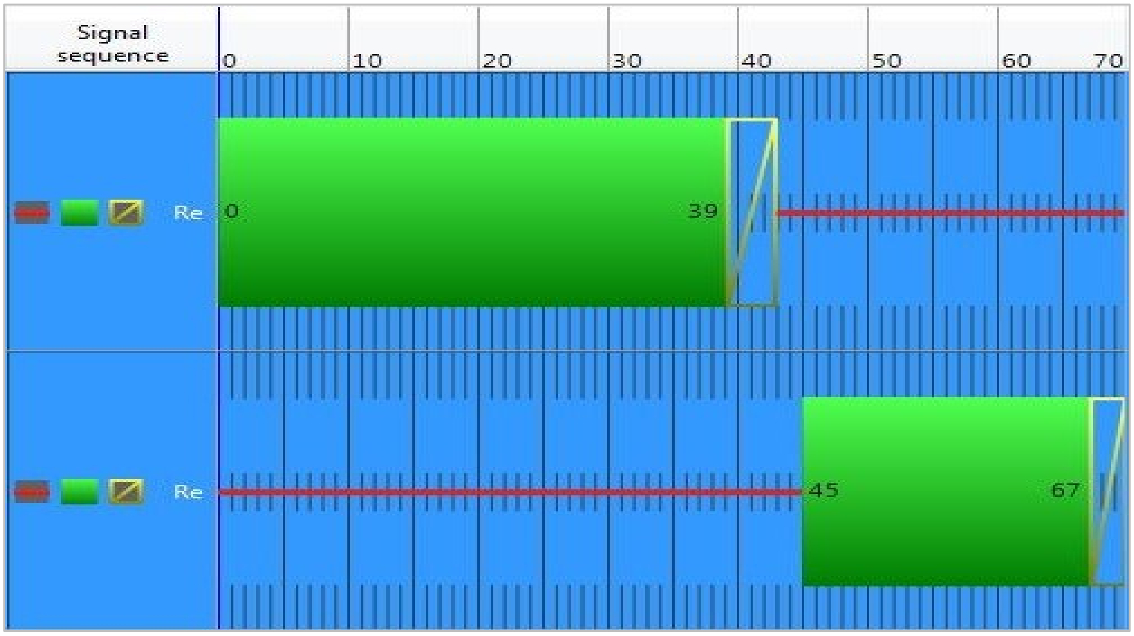


Figure 2-5 Signal Controller Modelled in VISSIM

Speed Profile

The desired speed is a primary factor during simulation to achieve the desired accuracy in regards to the replication of the real traffic condition. According to Nova Scotia Driver's Handbook, maximum speed in residential area is 50 km/hr. Therefore, a 40-50 km/hr. speed distribution was used for passenger cars while 30-40 km/hr. was used for heavy vehicles in the simulation model.

Priority Rules

Priority rules are meant for avoiding collision between two road users. One should yield to other users that has the right of way. Necessary priority rules were placed in the simulation model (see Figure 2-6 for example).

Conflict Area

An intersection encounters multidirectional traffic flow that pose threat of collision among vehicles. For example, left turning vehicles must yield for through vehicle. This conflicting movements are controlled by conflict area rules in VISSIM. In total, 1203 turning conflicts were resolved in the study model (See Figure 2-6 for example).

Final Transport Network

The final microscopic traffic network model consisting of 250 links, 570 connectors, 22 major intersections, stop signs, priority rules, and 1203 resolved turning conflicts is shown in Figure 2-6.

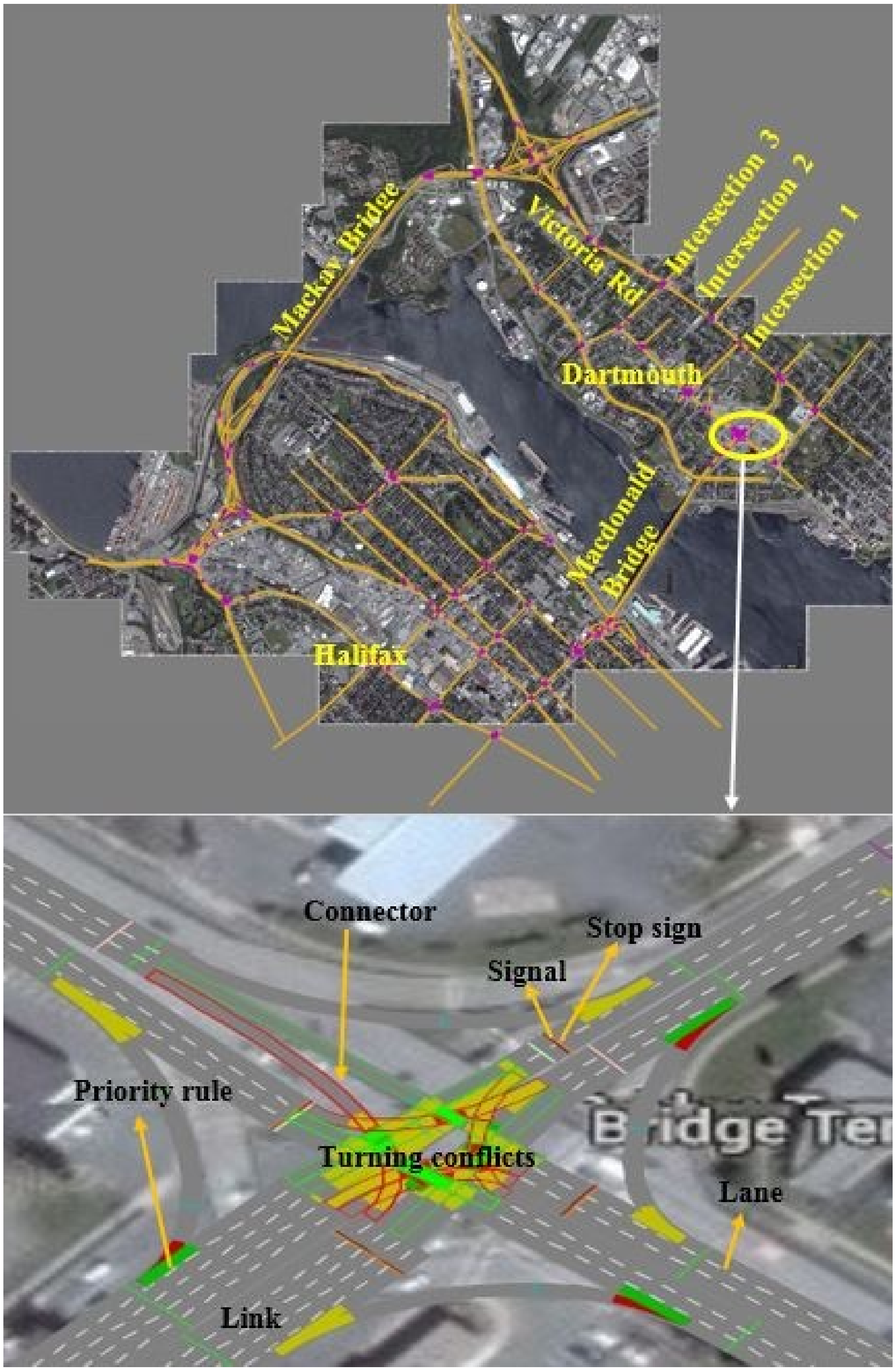


Figure 2-6 Traffic Microsimulation Network Model

2.3.4.4 Calibration and Validation of the Microsimulation Model

The basic principle of developing a microscopic traffic simulation model is to replicate the actual traffic network and traffic condition within the model *(Milam and Choa, 2002)*. In general, calibration includes the individual model calibration and general parameter calibration. In the absence of disaggregate traffic data (i.e. vehicle level speed profile), only calibration of critical parameters has been conducted using the aggregate data (i.e. traffic count). In this chapter, a static microsimulation model is developed based on the static routing decision, thereby omits the calibration of origin-destination (OD) travel demand matrix and route choice parameters. Only the driving behaviour parameters will be calibrated.

Traffic Assignment

Traffic flow is assigned in the network on the basis of field traffic count provided by HRM. This study used the time of the day distribution of the morning commute traffic flow based on the arrival and departure time distribution *(Megenbir et al., 2014)*. A warming period of 15 minutes was used for simulation. Initial simulation run resulted in lower traffic flow in the network. Necessary adjustments to traffic flow input is performed based on the comparison of simulated and observed traffic through an iterative process. The major calibration is done by calibration of the driving behavior parameters.

Driving Behaviour Parameter Calibration

The purpose of driver behaviour parameter calibration is to fine-tune a subset of driver behaviour parameters so that the model output matches field observed data *(Hollander and Liu 2008)*.

This study adopted the Wiedemann 74 car-following model in this study. For urban transport network, the Wiedemann 74 model has three car following parameters which are average standstill distance (ax_average), additive part of safety distance (bx_add), and multiplicative part of safety distance (bx_mult) *(Wiedemann, 1974; PTV, 2006; Olstam* *and Tapani, 2004)*. A good technical judgment on the ranges of the values of the parameters have been obtained from the literature. For example, standard average standstill distance is 1-3m *(Park and Schneeberger, 2003),* and range of additive part of safety distance, and multiplicative part of safety distance used in Cobb Parkway model calibration is 0-3 *(Miller, 2005).* Higher value of these three variables give a higher value of the following distance.

Initially, simulation runs have been conducted using the seed values of the parameters obtained from the literature *(Park and Schneeberger, 2003; Miller, 2005)*. The observed and simulated traffic flows are compared in order to evaluate the resemblance of the traffic flow in the simulation model. Several iterations were used for the calibration of the driving behavior parameters and were modified accordingly. For example, a lower car following distance value improves the network performance. Therefore, the value of each parameter is lowered by 10% for a reduced following distance. It is to be noted here that standard ranges are maintained during the lowering of the values of each parameter. Thus, the value of each parameter is varied and traffic flows are measured at screen line intersections and compared to the field traffic count. The combination of the parameters used for different trials of simulation are shown below in Table 2-9.

Table 2-9 Driving Behaviour Parameter Calibration

Combination #	Average standstill distance (ax_average)	Additive part of safety distance (bx_add)	Multiplicative part of safety distance (bx_mult)
1	3	2.8	2.85
2	2.7	2.5	2.6
3	2.4	2.2	2.3
4	2.1	1.9	2.0
5	1.8	1.7	1.7
6	1.5	1.4	1.4
7	1.2	1.1	1.1
8	1.0	0.8	0.9
9	1.0	0.5	0.7

For other general driving behavior parameters, the following standard values in Table 2-10 are used.

Table 2-10 General Parameter Calibration

General Calibration Parameters	Values
Lane Change distance	200 m
Look ahead distance	250 m
Look back distance	150 m
Minimum headway (front/rear)	0.5 m
Nos. of observed vehicles	4

Validation of the Microsimulation Model

The validation of the simulation model is evaluated in terms of GEH value, a modified chi-square statistics used by British guidelines *(UK Highway Agency, 1996)* and R^2 estimation for the different combinations of driving behavior parameters in Table 2-9. GEH is generally used for flow comparison and should be used to compare the hourly traffic flow. However, GEH can be computed from the following equation 11:

$$GEH = \sqrt{\frac{2\times(S - O)^2}{(S+O)}} \tag{11}$$

Where,

O = Observed traffic count, and S = Simulated traffic count.

Goodness of fit can be evaluated according to GEH values with the following criteria

GEH < 5; flows can be considered a good fit

5 < GEH < 10; flows may require further investigation

10< GEH; flows cannot be considered to be a good fit

In total twenty-two screen line intersections are selected for validation purpose (see Appendix A4). A set of targets were established to be achieved for selecting the successful combination of the parameters. The targets are mentioned as below:

- At least 80% of validated locations would have GEH value 5 or less

- R^2 would be greater than 85%. However, *Elseway (2010)* reported R^2 value as 88% during travel time estimation in urban areas.

Although GEH didn't achieve the goals absolutely, the final calibrated values of the parameters have been accepted for the combined attainment of the targets by the values of GEH and R^2. The final selected combination that gives the good fit of the model is combination #9 in Table 2-9 which gives the average standstill distance, additive part of safety distance, and multiplicative part of safety distance as 1.0, 0.5, and 0.7 respectively. The results of GEH and R^2 are shown in Table 2-11. The result shows that 69% of the locations selected for validation has GEH value less than 5, about 6% has in between 5 and 10, and 25% has greater than 10. The validation results suggest that 75% of the selected locations offer a good fit of the model. Moreover, R^2 has been found to be 87 % which is greater than the target value (80%). Therefore, this study considered the model as a reasonable representation of the observed traffic flow.

Table 2-11 Validation Results in terms of GEH and R^2 Values

Criteria	Values	
GEH	$GEH < 5$	69%
	$5<GEH<10$	6%
	$GEH > 10$	25%
R^2	87%	

2.4 Results and Discussions

Three alternative scenarios, specifically 1-hour delay, 2-hour delay, and 3-hour delay in re-opening the bridge in the morning are simulated for the morning rush hour, 5:30 am -9:30 am within the microscopic traffic simulation model. This study conducted a comprehensive traffic impact analysis on network as well as on link level. Mackay Bridge and Victoria Rd are considered for link level traffic impact analysis, as they are the main alternative paths in case of unscheduled closure of the MacDonald Bridge (Figure 2-6). Traffic impacts are evaluated in terms of changes in Measures of Effectiveness (MOEs). The link level MOEs considered include, average queue length, traffic flow. On the other hand, network level

MOEs include average delay, average speed, vehicle kilometers travelled (VKT) and traffic flow indicators.

2.4.1 Network Level Impacts

Table 2-12 shows traffic impacts on overall network resulting from the delays in re-opening the MacDonald Bridge. During the bridge closure, the increment in average delay and reduction in average speed indicate a growing congestion level in the network and delay increment in re-opening the bridge exacerbates the congestion. Interestingly, the increment in number of operating vehicles became steady at 30% with respect to scenario 2 (2-hour delay) and scenario 3 (3-hour delay), which means the system has exceeded the capacity and the congestion has reached its threshold. In this regard, it can be concluded that any further delay over 2 hours in re-opening the bridge will have a very small incremental changes to the impacts on the network. Moreover, the results suggest that total distance travelled by the vehicles also increases with the increase of bridge opening delays.

Table 2-12 Network Performance

Criteria	Base scenario (no delay)	Scenario 1 (1-hour delay)	Scenario 2 (2-hour delay)	Scenario 3 (3-hour delay)
Increment of operating vehicles (%)	-	12	30	30
Reduction of arrived vehicles (%)	-	8	9	17
Reduction of average speed (%)	-	5.2	11	17
VKT (km)	58225	59662	64648	60330

2.4.2 Average Travel Time and Average Delay

Average travel time and average delay are illustrated in Table 2-13. The results suggest that 1-hour delay in re-opening the bridge causes less traffic impacts in the network compared to other two scenarios. The simulation model reports an almost equal average travel time for both the base case scenario (no delayed opening) and scenario 1 (1-hour delay). However, in the case of scenario 2 (2-hour delay) and scenario 3 (3-hour delay), substantial traffic impact is observed as evident average travel time increases by 33% and 45% respectively with respect to the base case scenario. Moreover, the change in travel time (38.5 min to 49.17 min) with the increase in delays from 1 hour to 2 hours is relatively higher compared to that of from 2 to 3 hour which is 49.17 min to 53.67 min. This result confirms that 2-hour delay causes major disruptions for the network. Average delay also increases following the same pattern and it is around 47 minutes for 3-hour closure of the bridge.

Table 2-13 Average Travel Time and Average Delay during the Closure of the Bridge

Criteria	Base case (no delay)	Scenario 1 (1-hour delay)	Scenario 2 (2-hour delay)	Scenario 3 (3-hour delay)	Base case scenario Vs scenario 1	Base case scenario Vs scenario 2	Base case scenario Vs scenario 3
Average travel time (min)	36.9	38.5	49.17	53.67	4.3%	33.3%	45.4%
Average delay (min)	30	31.9	41.9	46.5	6.3%	39.7%	55%

2.4.3 Link Level Impacts

2.4.3.1 Impacts on the Mackay Bridge

The Mackay Bridge is one of the two major alternative paths between Downtown Halifax and Dartmouth. Table 2-14 summarizes the hourly traffic volume across the Mackay Bridge for both the base case (no delayed opening) and the unscheduled bridge closure scenarios. The results suggest that during 3-hour closure (5:30-8:30 am) of the MacDonald Bridge, total traffic volume across the Mackay Bridge (a perfect alternative of MacDonald Bridge) is found to be 2224 in the hour, 5:30 am- 630 am. Mackay Bridge accommodates 1197 re-routed vehicles in addition to its relatively low base traffic volume 1027 in this hour. However, during 6:30-7:30 am, Mackay Bridge carries a high traffic volume 2425 when the MacDonald Bridge is open. In total 676 number of re-routed vehicles could cross the Mackay Bridge during 6:30 am- 7:30 am which is only 31% of the total re-routed vehicles in that hour. As a result, the rest 69% of the re-routed traffic volume is ended up being in the network. This additional volume is added to next hours (7:30-9:30 am) given that 3rd hour (7:30-8:30 am) also contributes with additional re-routed traffic volume. Thus, congestion propagates at threshold level in the network.

In the case of a 2-hour bridge closure (5:30 am-7:30 am), a total of 1192 vehicles are shifted to the Mackay Bridge during 7:30-8:30 am (3rd hour) in spite of the MacDonald Bridge being operational in this hour. The reason is that during 2-hour (5:30-7:30 am) closure, the drivers have already made their route decision to take the Mackay Bridge and only 32% re-routed vehicles (695) could cross the bridge in the hour, 6:30-7:30 am. The rest is already assigned to the routes that takes to the Mackay Bridge. In addition, the comparison between scenario 2 and 3 shows almost same traffic volume shifted to the Mackay Bridge which indicates that congestion in the network reaches threshold level after 2 hour delays in re-opening the bridge. 1-hour bridge closure (5:30 am – 6:30 am) has the least impacts on the Mackay Bridge.

Table 2-14 Traffic Volume (vehicles / hour) on the Mackay Bridge

Time Interval	Base scenario (no delay)	Scenario 1 (1-hour delay)	Scenario 2 (2-hour delay)	Scenario 3 (3-hour delay)	Base scenario Vs. scenario 1	Base scenario Vs. scenario 2	Base scenario Vs. scenario 3
05:30-06:30	1027	2013	2244	2224	+986	+1217	+1197
06:30-07:30	2425	2445	3120	3101	+20	+695	+676
07:30-08:30	1055	1430	2247	2149	+375	+1192	+1094
08:30-09:30	1197	1571	1257	1257	+374	+60	+60

Figure 2-7 shows the visualization of traffic flows across the Mackay Bridge within the microsimulation model.

Figure 2-7 Traffic Flow across the Mackay Bridge

2.4.3.2 Queue Length

Three intersections on Victoria Rd including, (1) Boland Rd and Victoria Rd, (2) Woodland Ave and Victoria Rd, and (3) Albro Lake Rd and Victoria Rd (Figure 2-6) at Dartmouth side are selected to evaluate the congestion level in the vicinity of the MacDonald and the Mackay Bridge. The intermediate distances between the intersection 1 and its upstream intersection, intersection 1 and 2, and intersection 2 and 3 are 403 m, 297 m and 457 m respectively. Queue is measured at intersections to evaluate the degree of congestion on link level. In order to measure the queue length, we used a term 'saturated' which refers to a queue length equal to or more than the intermediate distance between two intersections. Otherwise, the value of the queue length is reported in Table 2-15. The result shows that intersection 1 is always saturated for the entire evaluation period (7:30-8:30 am) in the case of any scenarios due its proximity to the MacDonald Bridge.

The other two intersections (2 and 3), exhibits small queue length (i.e. intersection 3: at 8:00-8:10 am, queue length = 4 m, not even close to saturation) at all times due to 1-hour delay (5:30 am – 6:30 am) in re-opening the bridge. This is because, traffic flow in the network during 5:30 am – 6:30 am is significantly low, which is only 15% of the total trips within 5:30 am – 9:30 am.

In the case of a 2-hour bridge closure (5:30 am-7:30 am), intersection 2 & 3 are found saturated for the first 20 minutes of the evaluation hour (7:30 am -8:30 am). This is due to the re-routing of traffic from the MacDonald Bridge. However, the MacDonald Bridge becomes operational after 7:30 am. This again allows vehicles to cross the bridge and thereby gradually diminishes the queue saturation (i.e. intersection 3: at 7:50-8:00 am, queue length = 431 < intermediate distance -457m).

However, in the case of scenario 3 (3-hour delay), all of the intersections become saturated for the entire evaluation period and exhibits a highly congested traffic network. Hence, scenario 3 (3-hour delay) has led the network to exceed its capacity.

Table 2-15 Queue Length at Three Intersections

Intersections	Time Interval	Queue Length (m)			
		Base case scenario (no delay)	Scenario 1 (1-hour delay)	Scenario 2 (2-hour delay)	Scenario 3 (3-hour delay)
Boland Rd & Victoria Rd	7:30-7:40	saturated	saturated	saturated	saturated
	7:40-7:50	saturated	saturated	saturated	saturated
	7:50-8:00	saturated	saturated	saturated	saturated
	8:00-8:10	saturated	saturated	saturated	saturated
	8:10-8:20	saturated	saturated	saturated	saturated
	8:20-8:30	saturated	saturated	saturated	saturated
Woodland Ave & Victoria Rd	7:30-7:40	85	129	saturated	saturated
	7:40-7:50	59	55	saturated	saturated
	7:50-8:00	41	69	265	saturated
	8:00-8:10	38	110	174	saturated
	8:10-8:20	78	43	92	saturated
	8:20-8:30	46	107	82	saturated
Albro Lake Rd & Victoria Rd	7:30-7:40	6	8	saturated	saturated
	7:40-7:50	5	2	saturated	saturated
	7:50-8:00	3	4	431	saturated
	8:00-8:10	3	4	267	saturated
	8:10-8:20	2	4	2	saturated
	8:20-8:30	2	4	2	saturated

2.5 Summary

This chapter presents a framework for fuzzy logic-based risk assessment and microsimulation-based traffic modelling for assessing the traffic impacts due to construction related bridge opening delay. The study contributes to the gap existing in literature by assessing the traffic impacts induced by sudden delay in critical infrastructure renewal activities. Initially, the risk assessment has estimated the delay probabilities of bridge opening to the traffic depending on the level of consequences (i.e. low, medium, and high). For example, 1-hour delay probability in bridge opening ranges from 18%- 30% with a 40% probability for 3-hour bridge closure due to high level of consequence on re-decking activity. The delay risk analysis then feeds the microsimulation modelling with three bridge opening delay scenarios including (i) 1-hour delay (ii) 2-hour delay, and (iii) 3-hour delay in bridge opening.

Next, each delay scenario is considered for traffic impact assessment and results are compared to existing (no bridge closure) conditions. The microsimulation of the case scenarios yields considerable impact on link level as well as on network level. The Mackay Bridge, as a major alternative link, anticipates a high re-routed traffic volume during the closure of the MacDonald Bridge. The results reveal that only 31% re-routed vehicle could cross the Mackay Bridge in the hour 6:30-7:30 am due to a high peak hour volume on the bridge. As a result, queue grows rapidly and network gets saturated. This study found the queue length at each intersection along the Victoria Rd remains saturated for the whole evaluation period for 3-hour closure of the MacDonald Bridge. Moreover, scenario 2 (2-hour delay) and scenario 3 (3-hour delay) have shown 33% and 45% increment in average travel time respectively with respect to the base case scenario. In regards to the operational perspective, the change in number of operating vehicles became steady at 30% with respect to scenario 2 (2-hour delay) and scenario 3 (3-hour delay), which means the system has exceeded the capacity and any further delay over 2 hours in bridge operation would slightly change the impacts on surrounding network. Therefore, the congestion level that is found in terms of the changes in MOEs implies that the congestion reaches its threshold level in the absence of any warning of the closure incident.

This microsimulation model has certain limitations. For example, it considered a static assignment procedure which cannot capture the routing policies in congested transport network under time varying traffic demand. Therefore, this study develops a dynamic traffic assignment (DTA)-based microsimulation model in next chapter.

Nevertheless, this study contributes by offering a comprehensive framework for risk assessment and traffic simulation. Since the re-decking will continue further, the study could be a useful and practical simulation tool for practitioners. Particularly, static simulation has less computational burden unlike DTA considered in the next chapter.

Chapter 3

Dynamic Traffic Assignment (DTA)-based Microsimulation Modelling[2]

3.1 Introduction

Traditional microsimulation models described in the earlier chapter predict traffic flows based on deterministic static traffic assignment. One of the major shortcoming is that it doesn't capture dynamic route choice behaviour. Moreover, it cannot properly address the congestion spillback. In contrast, dynamic traffic assignment (DTA) process follows the principle of dynamic user equilibrium that assigns paths for a given origin-destination (OD). The DTA-based microsimulation models offer an opportunity to deal with continuously updating of routing choices in a stochastic transport network. They take into account the optimal route choice, depending on evolving traffic flows in the network. The main advantage of the DTA-based microsimulation models is that they can sufficiently incorporate drivers' stochastic route choice behaviour during sudden interruption in the network. The models estimate and evaluate network performance measures (travel time, delays, traffic flows etc.) based on the spatio-temporal information (i.e. incident locations, instance of incidence etc.). Therefore, this study expands the earlier microsimulation model by incorporating dynamic traffic assignment for traffic impact assessment. This chapter presents the dynamic traffic assignment-based microsimulation modelling framework that this study developed for sudden closure of the MacDonald Bridge.

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[2] This chapter is adapted from:

Alam, M. J., and Habib, M. A. "A Dynamic Traffic Assignment (DTA) Model to Assess the Traffic Impacts during Big Lift Project, Canada". *Presented at 51st Conference of Canadian Transportation Research Forum (CTRF), Toronto, Canada,* 2016, pp. 250-257.

3.2 Literature Review

The Dynamic Traffic Assignment (DTA)-based model is becoming a powerful tool in traffic microsimulation due to its capability in solving the long-standing problem inherited by traditional static traffic assignment methods. Static traffic assignment-based model lacks the ability to estimate the time-variant network performance measures (i.e. cost, traffic delay etc.). One of the main features of the DTA model is that it captures the dynamic diffusion of traffic flow through the stochastic network. They capture and implement complex interactions among vehicles, execute real time driver behaviour taking into account all spatial attributes (e.g. paths, lane change, etc.) and temporal aspects (e.g. instance of incidence, etc.). Hence, it gives a better traffic impact assessment which is important for adapting to the vulnerabilities and can be useful in understanding relevant impacts. Many studies started to investigate different DTA procedures. Several DTA-based models are available for planning applications. For instance, several DTA-based microsimulation models are VISTA *(Ziliaskopoulos et al., 2004)*, AIMSUN *(Barcelo and Casas, 2006)*, Dynameq *(Florian et al., 2006)*, Contram *(Taylor, 2003).*

The DTA-based simulation model estimates time varying link flow in the network and produce finer-grained time varying network performance with the aid of traffic dynamic simulation *(Florian et al., 2001)* which significantly contributes to understanding the traffic impacts in a greater detail. Several DTA procedure applications include the study of Stony Plain Road Bridge closure in Alberta. The results revealed that speed decreased by 5% to 15% and total vehicle delay hour increased by 8.8% to 35% *(Xin et al., 2014).* The DTA-based model DynaMIT-P was used for the evaluation of short term benefits of a strategy to reduce pollution and relieve traffic in Beijing *(Ben-Akiva et al., 2012)*. However, traffic impact assessment in the context of sudden bridge closure is limited. In this regard, DTA procedure appears to be the most suitable method for traffic impact assessment in case computational cost is not a concern. The model will efficiently incorporate driver behaviour and re-routing policies, which will offer better estimation of performance measures.

3.3 Methodology

3.3.1 Network Model and Data Used

The earlier static microsimulation model is converted into dynamic microsimulation model by adding necessary modelling features including zonal parking lots, nodes. Parking lots are used as origins and destinations. The link between two nodes are called edges. Sequence of the edges creates paths between a given pair of parking lot, i.e. OD pair. There can be multiple paths for a given OD pair. Initially, paths are created based on the default route choice model if that OD travel demand matrix is known. Then necessary modification is applied to the route choice parameters (see section 3.3.2.3) for a better replication of the observed traffic flow in the simulator.

However, static models do not need OD matrix. Traffic count was used for model development, calibration, and validation in the earlier chapter. The DTA-based model utilized the OD matrix obtained from a regional transport network model. The dynamic microsimulation-based approach uses OD matrix to assign the traffic in the network. The OD matrix obtained from Halifax Network Model *(Mahbubur and Habib, 2015)* is shown in Appendix A5. The obtained matrix contains traffic flows among 87 zones. This study constructed 13 super loading zones out of 87 zones within the microsimulation model. The adjacent zones that share the same major links are grouped into a single super loading zone (see Appendix A6). The super loading zones 1-4, and 8-11 generate incoming traffic flow from the zones external to the study area. The other super loading zones create intra-zonal traffic flows within the study area.

The final developed dynamic traffic microsimulation model consists of 613 links and connectors, 22 major intersections equipped with signal controllers, 13 super loading zones with 1275 origin-destination (OD) paths, 1203 resolved turning conflicts. The following Figure 3-1 and Figure 3-2 illustrate the different vehicle paths between a given OD pair.

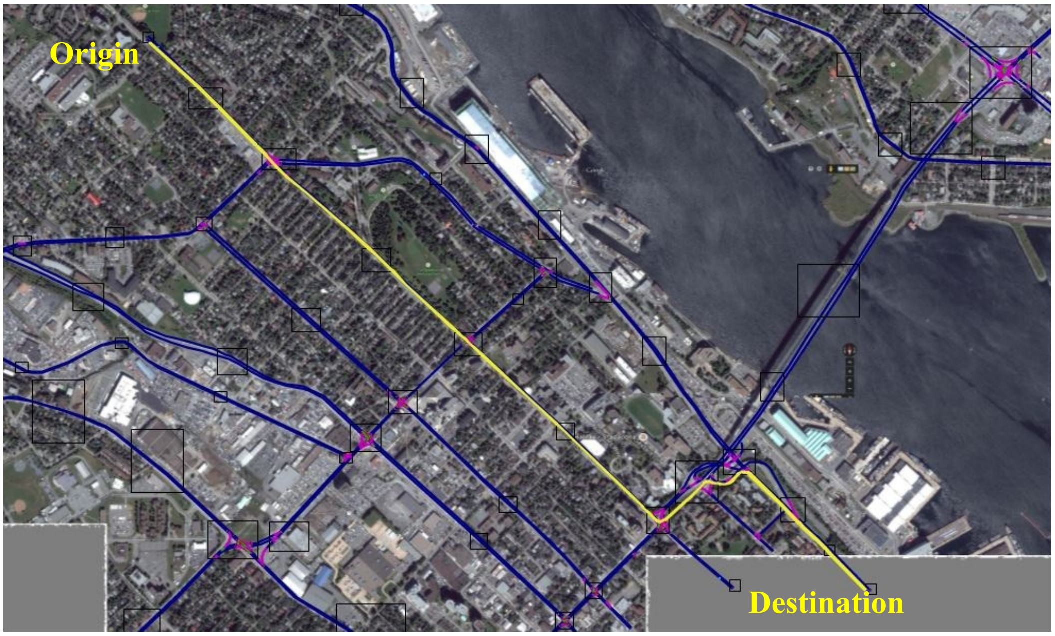

Figure 3-1 An Illustration of Vehicle Path between a Given OD Pair

Figure 3-2 An Illustration of Another Vehicle path between Same OD pair

3.3.2 Calibration of the DTA-based Model

This study implemented a DTA procedure within VISSIM platform that assigns all the vehicles through the transportation network. It uses the principle of dynamic user equilibrium procedures that assigns paths between their origin and destination if the origin-destination traffic demand, network topology are known.

The dynamic assignment (DA) process is implemented in the simulator using multiple iterations to assign the dynamic traffic flow in the network. The drivers go through an iterative process to optimize their route choice in the network. The drivers' learning through the DA process consists of sequential multi-step computations of travel paths, path general costs and path choosing probability. Travel paths are created depending on the traffic condition for multiple iterations. Therefore, more than one optimal path is created during the simulation. The criteria for the evaluation of the paths is general cost which consists of travel time, travel distance and others. Drivers evaluate available paths on the basis of trip cost and choose one path between a given origin-destination. Travel time cost is variable which can be derived only with the aid of simulation. The other two costs can directly be derived from the network topology. Path travel times are subjected to an updating process at each evaluation interval. Evaluation interval can be user-defined. A modified method of successive average (MSA) is used to compute the path travel times of the past iterations and compare it to path travel time of current iteration. The selection of a path is basically then a discrete choice problem. More details of dynamic process could be found in *PTV VISSIM 6.0 (2014).*

This study uses VISSIM to implement the DA process in the modelled network. Traffic has been assigned using the time of the day distribution of the morning commute traffic flow based on the arrival and departure Times distribution *(Megenbir et al., 2014)*. The simulation is conducted until there are no more significant changes in user defined convergence criteria from past iterations to current iteration. The calibration is performed starting with adjusting origin-destination (OD) matrix followed by the driving behavior parameter calibration. If the desired model accuracy is achieved, route choice calibration (local calibration) can be skipped.

3.3.2.1 OD Matrix Adjustment

The purpose of calibrating the DTA model is to minimize the deviation between the simulated traffic counts and the observed traffic counts as far as possible. A multiple iteration process in this kind of traffic volume-based calibration enables the OD matrix to be adjusted to fit the actual traffic data (i.e. traffic counts at intersections obtained from HRM). Necessary scaling and adjustment is performed to the OD matrix (see Appendix A5). Through an iterative process, two scaling factors 0.6 and 1.2 are applied to the traffic demand within the simulation hour 6:30 am -7:30 am, and 7:30 am – 8:30 am respectively to reduce the difference between the simulated and observed traffic counts. However, the major calibration of the model has been done by the calibration of the driving behavior parameters and the route choice parameter.

3.3.2.2 Calibration of Driving Behaviour Parameters

Standard calibration procedures are followed to determine the parameters for the dynamic traffic microsimulation-based model. Several iterations are executed for the calibration of the driving behavior parameters. Parameters are modified based on the outcome of each iteration. It shows that the lower the values of the parameters, the better the network performances. However, the values can be lowered until they do not cross the threshold values obtained from the literature *(Park and Schneeberger, 2003; Miller, 2005)*. For example, the value of each parameter is lowered by 20% for a reduced following distance and in total 6 sets of parameters are constructed (Table 3-1). Multiple iterations are conducted for each set of parameters and traffic flows are measured at scree line intersections (see Appendix A7) and compared to the field traffic counts.

Table 3-1 Driving Behaviour Parameter Calibration

Parameters	Average standstill distance (ax_average)	Additive part of safety distance (bx_add)	Multiplicative part of safety distance (bx_mult)
Set 1	2.4	1.5	1.7
Set 2	1.9	1.2	1.4
Set 3	1.5	0.96	1.1
Set 4	1.2	0.80	0.9
Set 5	1.0	0.60	0.7
Set 6	1.0	0.48	0.56

The simulation results suggest that set 5 and set 6 give the R^2 values as 0.64 and 0.60 respectively (see Appendix A8) which means further calibration of the driving behaviour parameters beyond set 5 degrades the goodness fit of the simulation model. Hence, driving behaviour parameter calibration is exhausted, and 24 links are still having higher traffic volume than observed it was decided to perform the route choice parameter calibration.

3.3.2.3 Route Choice Parameter Calibration

Calibration of route choice parameters causes changes to the traffic assignment results by changing some attributes, for example, link travel time. Local calibration is performed by adding link surcharge (i.e. cost components) to modify the assignment results. The surcharges are additional cost added to the general cost of the links. The provision is that the links that attract more traffic volume than observed will be penalized with a positive surcharge. In the absence of any well-defined guideline on the relationship between the surcharge value and the traffic divergence, a surcharge value of 30 is considered as the starting value. With each new local calibration surcharges, simulation was re-run until the model converges. Depending on the iteration results, surcharge values were modified and varied across the overflowed links. Finally, surcharge value 50 for 6 links, 100 for 7 links, 150 for 2 links, 200 for 6 links, and 500 for 3 links achieved an acceptable calibration.

3.3.3 Validation of the Model

The network performance after the calibration has been evaluated in terms of the minimum deviation between the simulated and observed traffic counts. Twelve screen line intersections have been selected for validation purpose. HRM field traffic data is used for validation. Figure 3-3 shows the correlation between the observed traffic count and simulated traffic count. The calibration result suggests that the R^2 value is 70% for the morning peak period which is a reasonable representation of the actual traffic flow in the model compared to other study stated earlier.

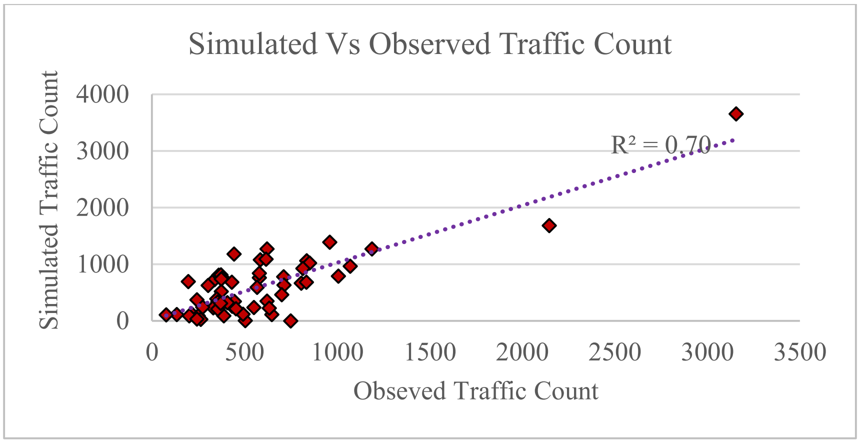

Figure 3-3 Traffic Assignment Calibration

3.4 Scenario Evaluation

A 4-hour bridge closure scenario (5:30 am -9:30 am) is simulated utilizing the calibrated and validated DTA model in this chapter. This study conducted a comprehensive traffic congestion analysis on network as well as on link level. The Mackay Bridge and Victoria Road are considered for link level traffic impact analysis for result illustration purposes. Traffic impacts are evaluated in terms of changes in Measures of Effectiveness (MOEs). The link level MOEs include average queue length and traffic flow. On the other hand, network level MOEs include average delay, average speed, vehicle kilometres travelled (VKT) and traffic flow indicators.

3.4.1 Network Performance

The traffic analysis results in Table 3-2 reveal that the MacDonald Bridge closure incident increases the total network delay with respect to the base case scenario. This is because 25% of vehicles could not reach the destination compared to the base case and ended up being in the network. As a result, the network operates under a saturated congestion and average delay increases by around 6 minutes with respect to base case. A reduction in average speed from 19.15 km/hr. (base case) to 15.78 km/hr. (bridge close) is also advocating the increase of traffic volume in the network.

Table 3-2 Network Performance

Performance Measures	Base Case	Bridge Close
Average speed (km/hr.)	19.15	15.78
Total Delay (hr.)	7625	9488
Average Delay (min)	10.8	16.5
Arrived Vehicle #	34015	25673

3.4.2 Local Traffic Impact Analysis

3.4.2.1 Impacts on the Mackay Bridge

Being one of the two most important CI of the Halifax transport network, the Mackay Bridge might be a major source of the bottleneck during the closure of the MacDonald Bridge in the morning peak period. Figure 3-4 presents a cumulative traffic volume (Dartmouth to Halifax) analysis across the Mackay Bridge for the base case and the unscheduled bridge closure scenario. The results suggest that the Mackay Bridge anticipates an additional 1200 vehicles during 5:30 am-7:30 am. This additional traffic represents only 21% of the total anticipated detoured traffic volume from the MacDonald Bridge during 4-hour period (5:30 am – 9:30 am). The rest 79% is yet to cross the Mackay Bridge in the next two hours (7:30 am-9:30 am).

However, the total 4-hour traffic flow across the Mackay Bridge during the bridge closure is found lower than that of the base case scenario. This result indicates that the capacity of the Mackay Bridge is underutilized during the closure of the MacDonald Bridge. The reason can be argued as the appearance of the spillover across the Mackay Bridge, originated at Windsor Street Exchange. This is the busiest intersection located at Halifax, immediately downstream of the Mackay Bridge (Figure 3-5). This intersection operates at full capacity during morning peak period maintaining a LOS E (see Table 3-3). On top of that the additional 1200 in traffic volume adds more delays to the intersections. As a result, LOS of Windsor Street Exchange degrades to LOS F. In summary, although the capacity exists, traffic flow declines across the Mackay Bridge due to spillover effects during the closure of the MacDonald Bridge.

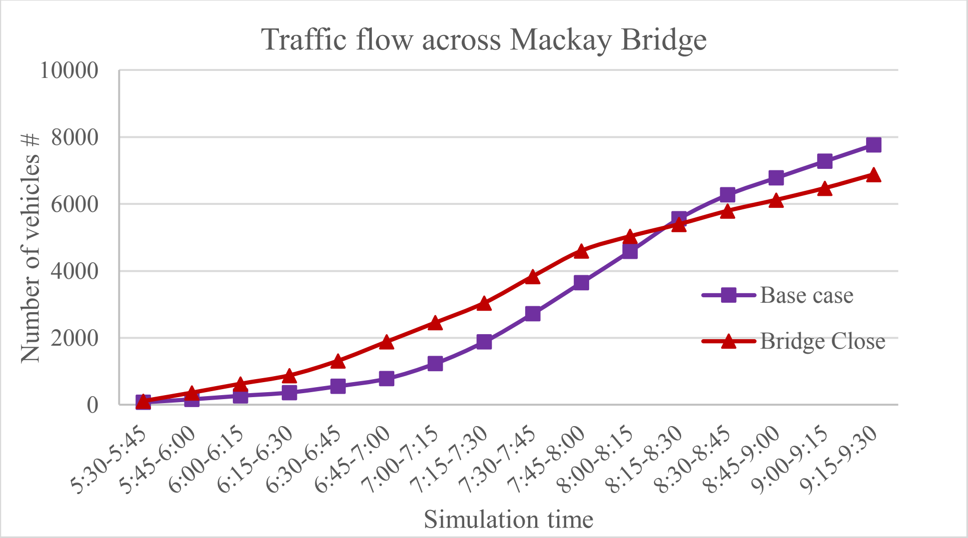

Figure 3-4 Traffic Impact on the Mackay Bridge

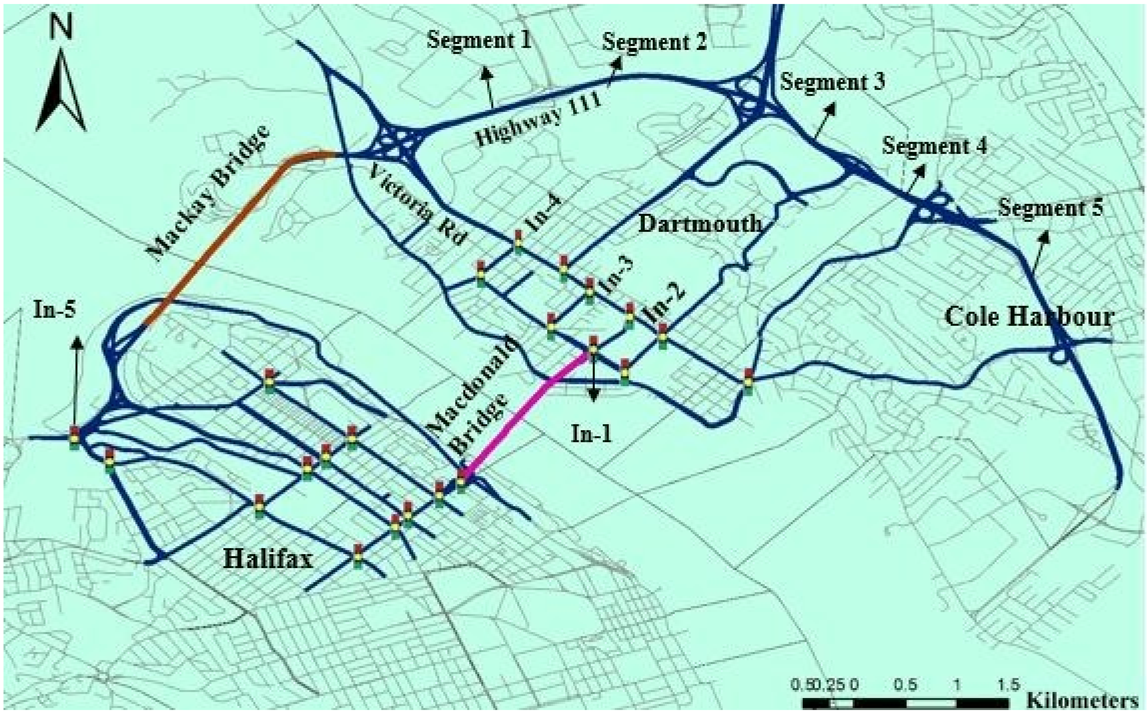

Figure 3-5 An Illustration of Halifax Transport Network

3.4.2.2 Performance of Critical Nodes

Table 3-3 presents the LOS of the intersections (In 1 to In 5 in Figure 3-5) and presents a comparison for both the base case and the unscheduled bridge closure scenario. Intersection, In-1 (Nantucket Avenue and Wyse Road) exhibits a LOS C during the bridge closure due to no traffic flow across the MacDonald Bridge. The other intersections, including Nantucket Avenue and Victoria Road (In-2), Boland Road and Victoria Road (In-3), and Albro Lake Road and Victoria Road (In-4) experience a greater detoured traffic volume during the bridge closure due to their proximity to the MacDonald Bridge. It is observed that surrounding key intersections, In-2, In-3, and In-4 in Dartmouth during the closure of the MacDonald Bridge operate with a high intersection delay compared to the base case and the LOS of these intersections lies in between E, and F. In-2, and In-3 operate at a LOS F during the closure which means that the traffic demand through these intersections exceeds the intersection capacity.

Table 3-3 Performance of Critical Nodes

Area	Intersection #	Name of Intersections	Base Case		Bridge Closure	
			Delay (sec)	LOS	Delay (sec)	LOS
Dartmouth	In-1	Nantucket &Wyse Rd	54.36	D	23.92	C
	In-2	Nantucket & Victoria Rd	42.8	D	133.71	F
	In-3	Boland &Victoria Rd	42.62	D	85.06	F
	In-4	Albro Lake & Wyse Rd	13.2	B	70.09	E
Halifax	In-5	Windsor Street Exchange	58.45	E	90.76	F

3.4.2.3 Impacts on Highway 111

This study evaluated multiple locations on Highway 111 for an in-depth understanding of the local traffic impacts in the network. Five segments (Figure 3-5), including segment-1 (between exit 2W and 3), segment-2 (between exit 3 and 4S), segment-3 (between exit 4 and 5), segment-4 (between exit 5 and 6), and segment-5 (between exit 6 and 7) are considered to investigate how the performance of Highway 111 could be affected by additional traffic volume (Figure 3-6) due to the closure of the MacDonald Bridge. Segment 1 and segment 2 are the immediate upstream sections of the Mackay Bridge on Highway 111 which exhibit a similar traffic flow as that of the Mackay Bridge (Figure 3-5). This is because the queue across the Mackay Bridge spreads along the immediate highway segments. The results in Figure 4 shows that traffic flow through segment 1 and 2 quickly approaches the yield point at around 8:00 am. There is no evident change observed in traffic flow through the segment 4 and segment 5 which indicate that capacity still exists at upstream highway locations. A proper traffic distribution through alternative routes at these very upstream locations could utilize this adaptive capacity during the bridge closure incident and thereby could improve the network efficiency.

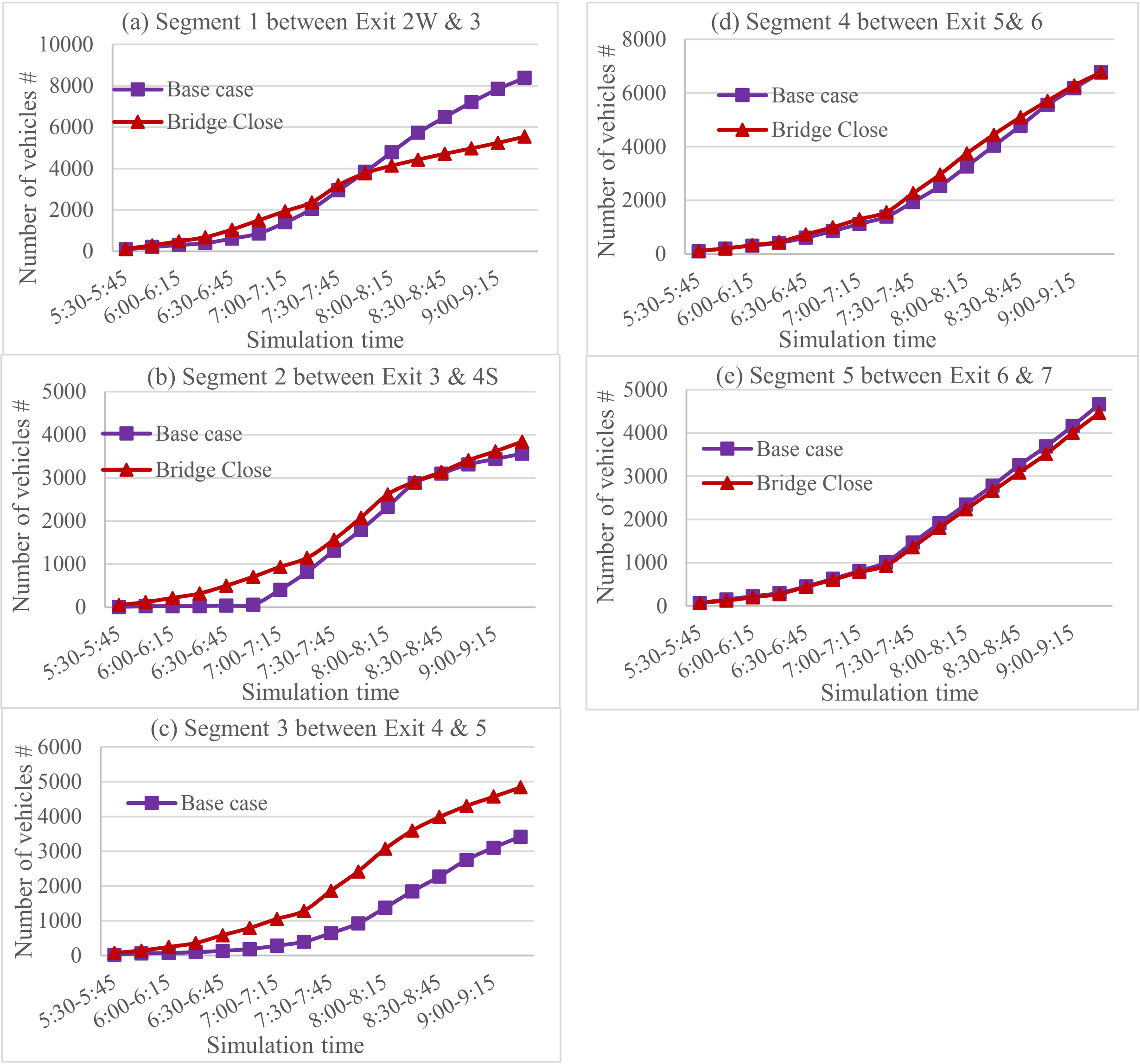

Figure 3-6 Cumulative Traffic Impacts on Multiple Segments of Highway 111 (Segment 1 is Close to the Mackay Bridge and Segment 5 is Near Cole Harbour (Figure 3-5))

3.5 Summary

This chapter presented a dynamic traffic assignment-based model to evaluate the traffic impacts during a 4-hour sudden bridge closure incident in the Halifax transport network. This study demonstrated that DTA-based model exhibits better behavioural representation due to dynamic route choice capability of the DTA model. Particularly, it takes into account spillover effects, which cannot be captured within the traditional static assignment-based microsimulation models. The simulation results yield substantial traffic impacts on the network as well as on link level. The incident increases the average delay by around 6 minutes and decreases the number of arrived vehicles by 25% with respect to base case. The Mackay Bridge, as a choke point, anticipates additional 1200 vehicles during the closure of the MacDonald Bridge within 5:30 am – 7:30 am. However, in total, the traffic flow across the Mackay Bridge declines with respect to base case scenario due to spillover from the downstream intersection of the Mackay Bridge. The results highlight that how vulnerable the network itself in the absence of adequate alternative routes. As a consequence, spillover appears on bridge surrounding links and critical intersections. The analysis of intersection performance suggests that Victoria Road operates under extreme traffic congestion during bridge closure as evident intersections operate at LOS E and F. The Windsor Street Exchange becomes grid-locked and operates at LOS F during closure period. Traffic queue also propagates along the Highway 111 as because of primarily depending on the Mackay Bridge. Interestingly, it has been observed that the there are not much variations in traffic flow at few upstream locations of Highway 111 which indicates that some adaptive capacity exists in the network.

The study has certain limitations. For instance, the developed DTA-based traffic microsimulation model does not consider departure time decisions of the drivers during making decisions regarding their trips which could give erroneous estimation of the traffic impacts. Therefore, this study develops a departure time choice model and incorporates it into the developed dynamic microsimulation model in the next chapter.

Chapter 4

Departure Time Choice Modelling for Dynamic Traffic Microsimulation[3]

4.1 Introduction

Departure time (DT) choice is a key component of decision making regarding daily trips. The interests in studying departure time choice has grown over the last decade due to the advancement in dynamic traffic microsimulation. The determination of the departure time choice is of paramount importance as traffic congestion is increasing dramatically in urban transport networks with an interest to adopt travel demand management (TDM) policies such as flexible office hours. Furthermore, the choice of departure time becomes critical during sudden risk occurrence as travellers might adjust their departure time in accordance to their schedule commitments. For instance, unscheduled closure of a bridge warrants adjustments of departure time if the traveller needs to arrive at his/her workplace on time. However, behavioral decision modelling of the departure time choice during sudden interruption in the network is not yet explored. Particularly, this type of departure time choice model should account for the travellers' risk seeking and/or risk averse attitudes in relation to their prior experiences. Therefore, this study proposed a Cumulative Prospect Theory (CPT)-based approach which appears to be compatible and advantageous to capture travellers' attitudes towards risk in choosing departure time. The study considers a special case for implementing the proposed model.

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[3] This chapter is adapted from:

Alam, M. J., and Habib, M. A. "Cumulative Prospect Theory-Based Departure Time Choice Modelling for Dynamic Traffic Microsimualtion.". *Under review for Transportation Research Board 96th Annual Meeting. Washington, D.C., U.S.A.,* January 08-12, 2017.

Since the construction began in October 2015, the MacDonald Bridge has already experienced multiple unscheduled closure and delayed re-opening in the morning (see Appendix 9). Understanding the traffic impact is of paramount importance given that the bridge might experience unscheduled closure again. *Alam et al. (2016)* examined the traffic impacts for partial and full closure in the peak hour. However, the study does not account for potential changes in departure time that the travellers in Halifax might consider given their constraints, such as scheduled activities and fixed arrival time at employment. The issue is more relevant as business establishments and employers do not have travel demand management (TDM) such as flexible work hour policies in place in the wake of this big construction project. Therefore, this study aims to develop a traffic simulation model that incorporates departure time choice dimension in order to better understand the resulting impacts on the transport network.

The study proposes a novel departure time choice model that follows Cumulative Prospect Theory (CPT) as travellers might react differently to changes for the choice of their departure time. The proposed modelling framework assumes that travellers will evaluate their departure time choice based on the travel times that they experience during prior unscheduled closure. The departure time model is then used to evaluate traffic impacts through a dynamic traffic microsimulation model.

4.2 Literature Review

Efficient mobility of a transportation system is greatly dependent on the satisfactory performance of the critical infrastructure (CI) within that transport network. Critical transportation infrastructure, i.e. bridges, are vital links that provide commuters with mobility and access to many facilities. The degree of social reliance on these CI consequently makes them critically vulnerable. Vulnerability creates the potential for disrupting the performance of these CI to an extent that could range from a very low level to cascading failure of the system. Cascading failure takes place when collapse of one element triggers failure of the other interconnected parts of the system *(Talukdar et al., 2003; Little, 2002)*. There are abundant examples in literature regarding the failure of CI including bridges and subsequent secondary impacts on the other parts of the network

(Ferguson, 2011; Xin et al., 2014; Xie and Levinson, 2011). Most of these studies used a microsimulation approach for traffic impact assessment. The main advantage of the use of microsimulation is that it is capable of representing multiple transportation choice dimensions such as departure times, routes, modes and destinations *(Arentze and Timmermans, 2003)*. Additionally, microsimulation models efficiently capture the interaction between the individual decision maker and the performance of the overall transportation system.

Despite many advantages of the microsimulation models as described in earlier chapter, earlier studies hardly have an explicit component that incorporates departure time choice decision within the simulation platform. Few microsimulation models *(Van der Mede et al., 1993; Hu and Mahmassani, 1997; Rossetti and Liu, 2005)* account for the departure time choice dimension. The shortcoming of these studies is that they did not consider travel time uncertainty in modelling departure time choice decisions. Most importantly, how Travellers might react to uncertainty in making departure time choice is limited in the existing literature *(Ettema and Tamminga, 2005)*.

In contrast, many studies focused on modelling route choice decision under uncertainty. Gao et al. *(Gao et al., 2010)* examined Travellers' strategic route choice behavior in response to revealed traffic condition in a stochastic network. They used cumulative prospect theory (CPT) that accommodates flexible risk attitude to capture Travellers' within-day adaptive route choices. The study revealed that in the case of certain losses, Travellers prefer taking a riskier choice. Ben-Elia and Shiftan *(Ben-Elia and Yoram, 2010)* developed a learning based route choice model that investigates the effects of information provided in real time. This study concluded that information and experience have a combined effect on drivers' route choice behavior. In addition, informed drivers are risk seeking Travellers compared to the non-informed drivers. On the other hand, another study by Avineri and Prashker *(2006)* shows that risk averse attitude is dominant for route choice decision with static prior pre-trip information.

Studies in relation to choice under risk has evolved dramatically in recent years in economics and transportation *(Gao et al., 2010; Tverskey and Kahneman, 1992; Kahneman and Tverskey, 1979; Barberis et al., 2016)*. In the case of departure time choice, majority of the studies examined fixed attitudes towards uncertainty *(Ettema and Tamminga,, 2005; Hendrickson and Plank, 1984; Small, 1982)*. Consideration of flexible attitudes requires understanding of differential responses towards the gains and losses in relation to a reference point, for instance, typical travel time, work start time and arrival time. This framing issue was partly addressed by Mahmassani and Chang (*1987*) that introduces ‘indifference band’, a tolerable late schedule delay, which is the difference between the preferred arrival time (PAT) and the actual arrival time. The flexible response under uncertainty is further investigated by several studies in recent years using prospect theory. For instance, Jou et al. *(2008)* applied a prospect theory-based approach to examine how auto users utilize the arrival time information in daily departure time choice taking into account the asymmetric responses of the drivers towards gains and losses. Prospect theory is a non-Expected Utility (EU)-based theory which addresses the violations of few assumptions held by mainstream models of Travellers’ behavior. Other non-EU-based theory include, Cumulative Prospect Theory *(Tverskey and Kahneman, 1992)*, Fuzzy Logic *(Zadeh, 1965),* Elimination by Aspects *(Tverskey, 1972),* etc. that address limitations of the EU theory. CPT is argued as the most preferred non-EU model *(Strammer, 2000)* which is an extension of the original prospect theory that sufficiently accommodates the attitudes of decision makers towards risky prospect *(Quiggin, 1982; Yaari, 1987).* It captures the cognitive bias in which people make inconsistent choices depending on their own perception obtained from the experience. In a nutshell, it adopts a limited rationality approach to predict the Travellers’ responses to unexpected, sudden and risky outcomes. The CPT is in alignment with the departure time choice context considered in this study which poses considerable uncertainty for the Travellers in the morning rush hours. Therefore, the objective of this study is to develop a framework in order to model the departure time choice when a network is exposed to uncertain risk events for a longer period of time.

4.3 Methodology

Departure time choice primarily depends on anticipated travel time and preferred arrival time (PAT) for daily activities. Travellers depart from home aiming to avoid delays in their schedule. An individual chooses his/her departure time in such a way that it is as close as possible to a preferred arrival time (PAT). Therefore, departure time (DT) can be expressed as follows:

$$DT = f\ \left(t,\ T_t,\ PAT\right) \tag{1}$$

Where,

t is trip start time

T_t is trip travel time at t

PAT is preferred arrival time

PAT can be defined by the typical arrival time in morning rush hour. T_t depends on the traffic conditions, including uncertainty and Travellers' experience. Let's assume, if E_t represents the Travellers' experience in the network, then it can be written as follows:

$$E_t = \left(x, p, w, t\right) \tag{2}$$

Where,

E_t is a vector of attributes describing the experience

x is the outcome of the experience

p represents the probability of outcome, x

t is a temporal attribute (i.e., departure time)

w is a spatial attribute (i.e., origin, i, destination, j)

It is assumed that a traveller perceives travel time loss or gain by comparing his/her travel time for a bridge closure incident against travel time on a typical day (i.e. no bridge closure scenario). The outcome, x could be either travel time loss or gain. If a set of individual travel time in no bridge closure event is T_{base} and in bridge closure event is $T_{incident}$, then the following two sets of travel time could be obtained:

$$T_{base} = \{T_{b1}, T_{b2}, T_{b3} \ldots\ldots\ldots\ldots T_{bn}\},\ n \in N \tag{3}$$

$$T_{incident} = \{T_{i1}, T_{i2}, T_{i3} \ldots\ldots\ldots\ldots T_{in}\},\ n \in N \tag{4}$$

Then, the difference between two travel times can be calculated as follow:

$$x = \{T_{incident} - T_{base}\} \tag{5}$$

Which can be termed as travel time 'loss' or 'gain', where

$$x = \begin{cases} Loss, & if\ (T_{incident} - T_{base}) > 0 \\ Gain, & if\ (T_{incident} - T_{base}) < 0 \end{cases} \tag{6}$$

In this study, attribute E_t can be regarded as the experience in terms of travel time loss/gain. In terms of departure time choice, it is assumed that a Traveller will evaluate the travel time loss or gain and its probability of occurrence. For the sake of simplicity, this study assumed time segments, d_i at 15-minute interval as the departure time choice set for Travellers. For a given origin-destination (OD) pair, a Traveller will revise the choice of departure time based on his/her perception of the uncertainty associated with unscheduled closure of the bridge and resulting impacts on their travel time.

For a given OD pair, this study assumes that a Traveller will react differently to travel time losses and gains following the Cumulative Prospect Theory (CPT) principle. The CPT model perceives the utility of choosing a departure time segment, d from the departure time choice sets. It models the perceptions jointly with a value function and a weighting function. Let's assume, if a Traveller chooses the departure time segment, d which yields an outcome, x_q with a probability p_q. Then the uncertain prospect f for the choice can be identified as (x_q, p_q). The value of each outcome then can be calculated using the following parametric formula proposed by Tversky and Kahneman *(1992)*.

$$v(x_q) = \begin{cases} x_q^{\alpha}, & if\ x_q > 0 \\ -\lambda(-x_q)^{\beta}, & if\ x_q \le 0 \end{cases} \tag{7}$$

The parameter $\alpha \le 1$ and $\beta \le 1$ measure the degree of diminishing sensitivity and $\lambda \ge 1$ describes the degree of loss aversion. The value function is concave for gain and convex for losses.

The probability weighting function that model distortions in decision making takes the following equation:

$$w^+(p_q) = \frac{(p_q)^\gamma}{[(p_q)^\gamma + (1-p_q)^\gamma]^{1/\gamma}} \quad w^-(p_q) = \frac{(p_q)^\delta}{[(p_q)^\delta + (1-p_q)^\delta]^{1/\delta}} \tag{8}$$

Where, p_q represents the probability of qth outcome (i.e. loss/gain) during choosing departure time segment d . A positive sign is for gain and a negative sign is for loss outcome. Figure 4-1 and Figure 4-2 show a theoretical value function and a weighting function respectively.

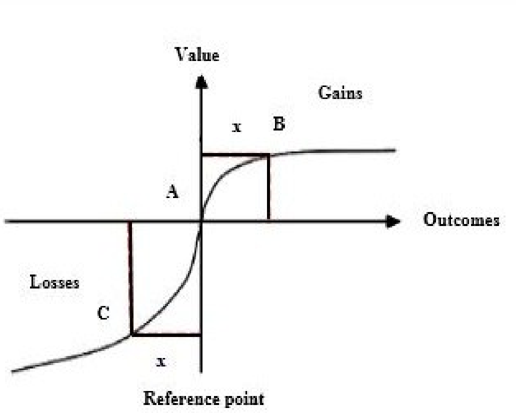

Figure 4-1 Value Function of CPT

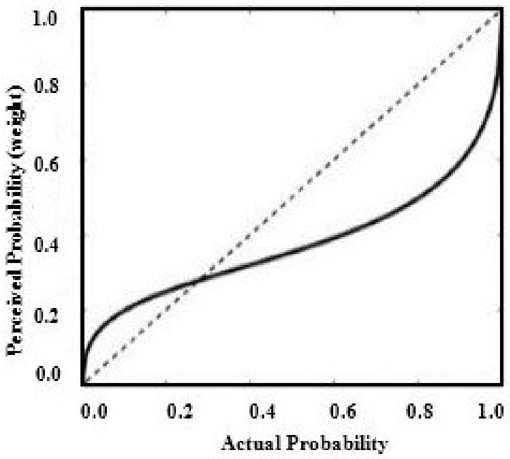

Figure 4-2 Probability Weighting Function

The utility of the positive prospect, f^+ and negative prospect, f^- are then written as:

$$CWV(f^+) = \sum_{q=0}^{n} \pi_q^+ v(x_q) \text{ and } CWV(f^-) = \sum_{q=-i}^{0} \pi_q^- v(x_q) \tag{9}$$

Where, the decision weighting factors, π^+ and π^- are calculated from the weighting functions of cumulative probabilities given that the outcomes are arranged in an increasing order.

$$\pi_q^+ = w^+(P_q + ... + P_n) - w^+(P_{q+1} + ... + P_n); \quad 0 \le q \le n-1, \ \pi_n^+ = w^+(P_n) \tag{10}$$

$$\pi_q^- = w^-(P_{-i} + ... + P_q) - w^-(P_{-i} + ... + P_{q-1}); \quad 1-i \le q \le 0, \ \pi_{-i}^- = w^-(P_{-i}) \tag{11}$$

Furthermore, this study introduced a general logarithmic term in estimating the probability that individual, z selects a departure time segment, d in choice set in order to correct the individual's flexibility of departure at any instance within the departure time segment interval. The model can be defined according to Gao *(2005)* as follows:

$$P(d \mid D;\psi) = \frac{e^{V_{dz}}}{\sum_{l \in dz} e^{V_{lz}}} \tag{12}$$

Where, $V_{dz} = \theta \ln(depsegmentsize) + CWV_{dz}$. CWV_{dz} is the CPT utility value calculated using equation *(7)* to equation *(11)* for the choice of departure time segment d and individual z. ψ is the vector of parameters $\beta, \lambda, \delta, \theta$. λ does not have any effect on the ordering of the utility in a loss only situation so it is assumed as 1. β and δ are assumed as 0.88 and 0.69 respectively *(Gao et al., 2010)*.

Thus, the CPT-based departure time choice model generates revised departure times which estimates the traffic flow in the network in response to sudden bridge closure incident within a traffic microsimulation model.

4.4 Application of the Proposed Framework

4.4.1 Microsimulation Model

In the earlier chapter, a dynamic microscopic traffic simulation model was presented to simulate the scenario regarding the closure of the MacDonald Bridge in order to evaluate traffic impacts on the surrounding network. The shortcoming of this simulation model was that departure time was not explicitly modelled to assign the traffic in the network. In this study, we are extending our earlier model, by explicitly incorporating a departure time choice component within the simulation framework. This integrated modelling framework accounts for the uncertainty in travel time, utilizing information from earlier experiences to update the departure time accordingly.

This study uses a dynamic traffic assignment (DTA) modelling framework as it efficiently estimates the time varying link flow in the network and evaluate the time varying network performance with aid of traffic dynamic simulation *(Florian et al., 2006)*. The study area includes all the arterial roads, few important collector roads, two bridges, and Highway 111 in Halifax. The network model consists of 613 links and connectors, 22 major intersections equipped with signal controllers, 13 super loading zones giving 169 OD pairs, 1275 origin-destination (OD) paths, 1203 resolved turning conflicts and other important road network features (i.e. priority rules, reduced speed areas). Road geometry information such as number of lanes, grades, direction and turning movements are collected from Google Earth, Google Street View, and Halifax Regional Municipality (HRM) Geodatabase, 2012.

Signal time has been obtained from the Public Work Traffic Study of Halifax Regional Municipality (HRM), October 2014. Moreover, the origin-destination (OD) traffic demand for the morning commute period has been obtained from the Halifax Network Model *(Mahbubur and Habib, 2015)*. The microsimulation approach used the time of the day distribution of the morning commute traffic flow based on the arrival and departure time distribution *(Megenbir et al., 2014)*.

4.4.2 Departure Time Choices and CPT Utilities

During the implementation of the departure time choice within a microsimulation platform, in total, eight departure time segments (d_1 to d_8) are considered within 6:30 am – 8:30 am at 15-minute interval. Travel time losses/gains are estimated for each segment from the output of the simulation of the bridge closure scenario. Simulation results suggest a loss only situation. On the other hand, few individuals who live in Halifax Peninsula observe slight gains. Travel time losses and their probabilities are estimated for all OD pairs (see Appendix A10). For example, Table 4-1 illustrates the travel time losses and probabilities for each departure time segment in case of OD pair, 1-4.

Table 4-1 Departure Time Segments, Travel Time Losses, and Associated Probabilities for OD Pair, 1-4

		6:30 am – 7:30 am		
Departure time segments, d_i	Segment d_1 (6:30 am – 6:45 am)	Segment d_2 (6:45 am – 7:00 am)	Segment d_3 (7:00 am – 7:15 am)	Segment d_4 (7:15 am – 7:30 am)
Travel time losses, x_q (min)	4	8	8	8
Probability, p_q	0.59	0.41	0.95	0.95
		7:30 am -8:30 am		
Departure time segments, d_i	Segment d_5 (7:30 am – 7:45 am)	Segment d_6 (7:45 am – 8:00 am)	Segment d_7 (8:00 am – 8:15 am)	Segment d_8 (8:15 am – 8:30 am)
Travel time losses, x_q (min)	24	32	36	36
Probability, p_q	0.55	0.78	0.4	0.4

Next, choice set for the drivers of each departure segment is determined and the prospects for each choice in the choice set is calculated using probabilities of losses. For instance, if travel time loss for the drivers who belong to d_i is x_i with a probability p_i, and loss at departure time segment d_{i-k} is x_{i-k} with a probability p_{i-k} for a particular OD pair, $i-j$ where $k \in N$, then the departure time choice can be named as 'd_i to d_{i-k}' and the prospect can be written as $\left(x_{i-k}, p\right)$, p can be obtained as the product of p_i and p_{i-k}. In total 15 departure time choices create a choice set for each OD pair. Afterwards, the value of each prospect is calculated using the value function in equation (7) and the weighting factor is obtained using equation (8) and equation (11). The CPT utility, CWV is then calculated by multiplying the values of the prospect with the weighting factor (for detailed calculation, see Appendix A11). For example, Table 4-2 shows the choice set, prospects, and CPT utilities for OD pair, 1-4.

Table 4-2 Departure Time Choice Set, Prospects and CPT Utilities for OD Pair, 1-4

Choices	Prospects (x_q, p_q)	CPT Utility (CWV)	Choices	Prospects (x_q, p_q)	CPT Utility (CWV)
d_2 to d_1	(-4, .24)	-0.97	d_5 to d_4	(-8, .53)	-5.63
d_3 to d_1	(-4, .56)	-1.67	d_6 to d_3	(-8, .59)	-3.86
d_3 to d_2	(-8, .39)	-2.4	d_6 to d_4	(-8, .59)	-3.86
d_4 to d_1	(-4, .56)	-1.67	d_6 to d_5	(-24, .39)	-6.72
d_4 to d_2	(-8, .39)	-2.4	d_7 to d_4	(-8, .35)	-2.36
d_4 to d_3	(-8, .90)	-4.85	d_7 to d_5	(-24, .23)	-4.8
d_5 to d_2	(-8, .23)	-1.72	d_7 to d_6	(-32, .26)	-7.1
d_5 to d_3	(-8, .52)	-2.92			

4.5 Results and Discussions

4.5.1 Departure Time Choice under Uncertainty

This study follows a CPT framework which identifies how drivers would react to a sudden closure of the bridge. The drivers evaluate their departure time choices based on their objective of reaching a destination at a fixed arrival time. The CPT model works better than an Expected Utility (EU)-based model in this case, as the EU model only considers minimum travel time criteria to select the departure time regardless of other aspects. For instance, optimization of the choices to reduce general cost and discomfort, i.e. very early departure or very early arrival. Table 4-3 shows the departure time choices for the drivers of OD pairs, 2-9 and 1-9 those usually depart at departure time segment d_4. The results suggest that drivers should prefer departure time segment d_1 according to EU. If so, they need to depart from home 45 minutes earlier with respect to their usual departure time. On the other hand, CPT-based choices suggest that drivers should prefer departure time segments, d_3 and d_2 in the case of OD pair 2-9 and 1-9 respectively, which deviates from the EU results. Moreover, it can be asserted from the results in Table 4-3 that drivers prefer relatively certain lower loss and higher loss with low uncertainty. Econometric models and other traffic assignment models *(Ettema and Tamminga, 2005)* fail to interpret this risk attitude based only on expected travel time and its variance.

Table 4-3 Departure Time Segment Choice by the Drivers of Segment d_4, OD Pairs, 2- 9 and 1-9

OD pairs	Choices	Expected average travel time (min)	Travel time loss (min)	Probability	CPT utility (CWV)
2-9	d_4 to d_1	10.5	12	0.45	-5.58
	d_4 to d_2	13	12	0.46	-5.62
	d_4 to d_3	12.5	8	0.65	-5.24
1-9	d_4 to d_1	11	12	0.49	-6.40
	d_4 to d_2	15	12	0.40	-5.95
	d_4 to d_3	13.5	8	0.89	-6.84

4.5.2 Traffic Impact Results

4.5.2.1 Network Capacity

Table 4-4 presents the network capacity analysis for two models including model 1 which does not include a departure time (DT) component and model 2 that includes a DT component. The results from model 2 suggest that travel demand shifts to the earlier departure time segments. However, the total number of arrived vehicles in model 1 and model 2 is almost equal which is around 12,600 vehicles. Therefore, more vehicles ended up being in the network and travel demand increases by 5235 vehicles (the difference between total operating vehicles in model 1 and model 2 in Table 4-4) in the network after the inclusion of the departure time choice decision into traffic microsimulation. The model 2 results reveal that both the operating capacity and the discharge capacity of the network are fully utilized during the closure of the bridge. Therefore, it can be asserted that the traffic microsimulation without the DT component could perform erroneous estimation of the traffic impacts as travellers adjust their departure time alongside with taking route choice decision.

Table 4-4 Network Capacity before and after the Inclusion of Departure Time (DT) Choice Component into Traffic Assignment Model

Departure time Segments	Model 1 Without DT component		Model 2 With DT component	
	Operating vehicles	Arrived vehicles	Operating vehicles	Arrived vehicles
6:30-6:45 (d_1)	1329	1044	1699	1699
6:45-7:00 (d_2)	1608	1359	1348	2348
7:00-7:15 (d_3)	1821	1365	2608	2608
7:15-7:30 (d_4)	1968	1400	2719	2719
Total	6726	5168	9374	5358
7:30-7:45 (d_5)	5124	1717	5766	5766
745-8:00 (d_6)	6425	1945	7010	7010
8:00-815 (d_7)	7459	1846	8024	8024
8:15-8:30 (d_8)	8318	1897	9113	9113
Total	27326	7405	29913	7241
Grand Total	34052	12573	39287	12599

4.5.2.2 Average Traffic Delay

The model 2 results exhibit a significant increment in average traffic delays in the period of 6:45 am - 7:45 am with respect to model 1 as shown in Figure 4-3. This is due to individuals switching to the early departure time segments to avoid late arrival; consequently, collective decision worsens the overall traffic condition in the network. During the rest of the period (7:45 am - 8:30 am), average traffic delay keeps increasing in the case of both models; however, the delay value is higher in the case of model 2. The increment in total traffic delay within 6:30 am – 8:30 am reported by model 2 with the DT component during the closure of the bridge is 2094 hours with respect to no bridge closure scenario. The DTA-based microsimulation model developed in the earlier chapter was used to test the no bridge closure scenario. It has been observed that model 2 with the DT component estimates additional 942 hours in traffic delay within this period with respect to model 1 without the DT component. Hence, model 1 may underestimate the average delay in the absence of a DT component during traffic flow analysis.

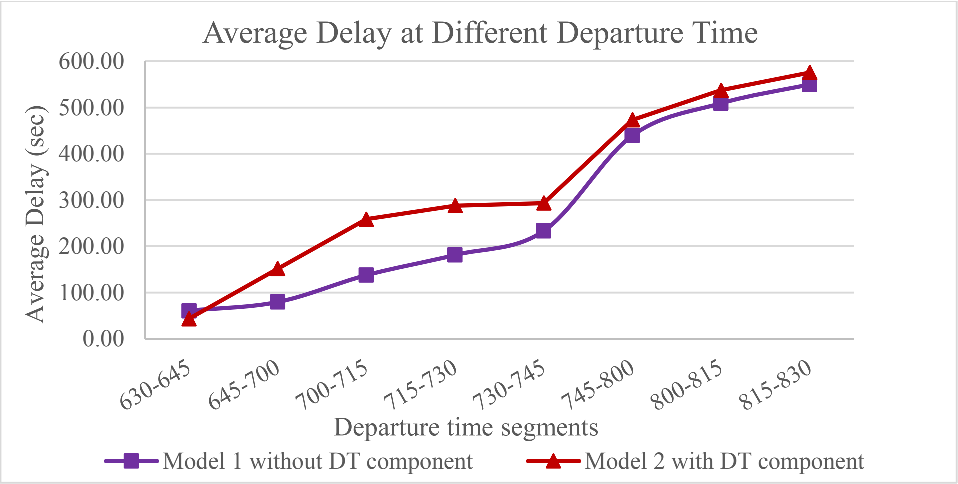

Figure 4-3 Average Traffic Delay before and after DT Choice Inclusion into Traffic Microsimulation

4.5.2.3 Local Traffic Impacts

This study evaluated multiple locations to understand the local traffic impacts. For instance, queue length is observed at bridge nearby intersections including, (1) Boland Rd and Victoria Rd (2) Woodland Avenue and Victoria Rd (3) Albro Lake Rd and Victoria Rd (Figure 2-6) in the case of both models, i.e., model 1 and model 2. It has been observed that queue length reduces in the case of model 2 (Figure 4-5 and 4-6). The results suggest that travellers avoid critical points based on their experience in the case of model 2 which includes a DT component. Model 2 with a DT component is capable to analyze the evolving adaptive capacity in the network which was not revealed in model 1 without the DT component. Additionally, more vehicles cross the Mackay Bridge (Figure 4-8) at the early departure time segments. In consequence, queue length starts to reduce after 7:45 am.

In a nutshell, localized traffic impacts are not uniform throughout the network. All localized impacts aggregately give overall network performance. Though the overall network performance degrades, traffic condition at Dartmouth road network improves. The model 2 with the DT component reveals that local network performs better; hence, if we do not include the DT choice dimension into simulation model, specifically the CPT-based departure time choice model, it could offer inaccurate estimates of performance measures.

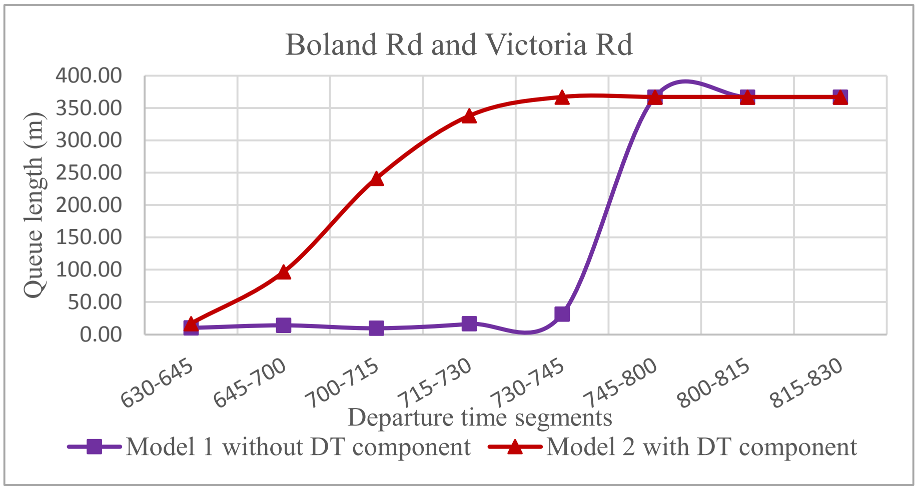

Figure 4-4 Queue Length at Boland Rd and Victoria Rd

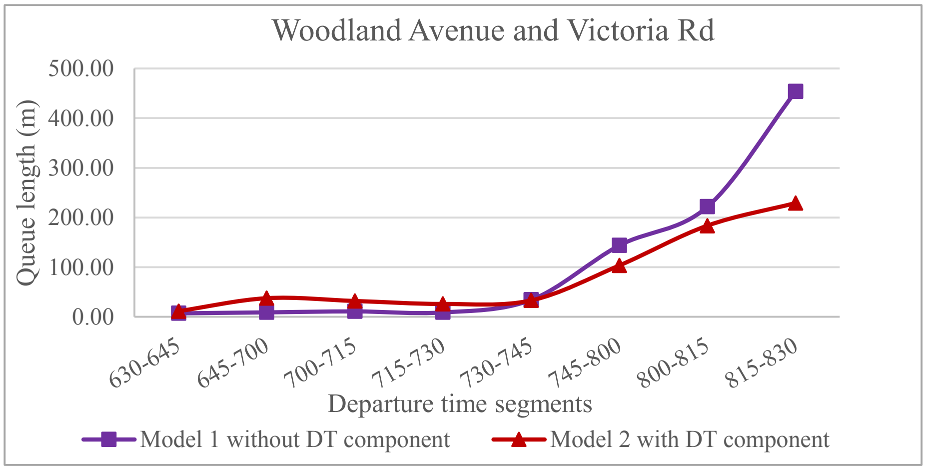

Figure 4-5 Queue Length at Woodland Avenue and Victoria Rd

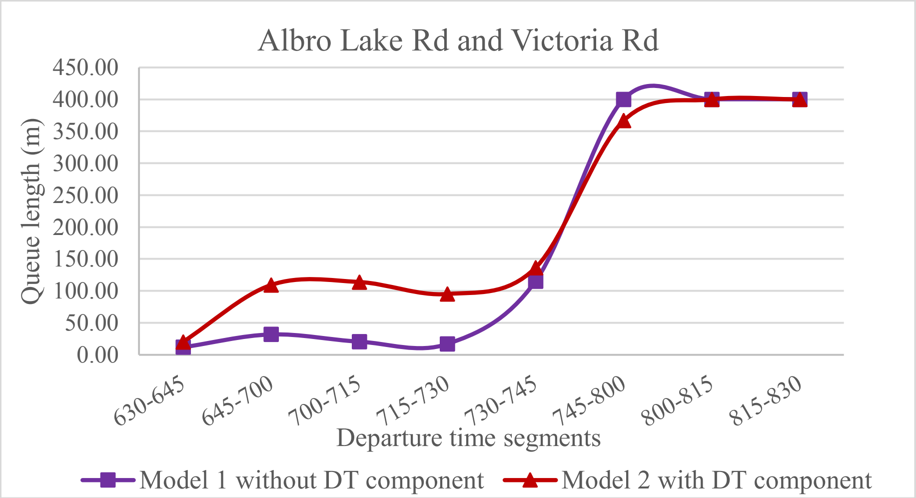

Figure 4-6 Queue Length at Albro Lake Rd and Victoria Rd

The following Figure 4-7 illustrates the queue build up at the intersection "Woodland Avenue and Victoria Rd" during the bridge closure.

Figure 4-7 Queue Build Up in Traffic Microsimulation Network Model

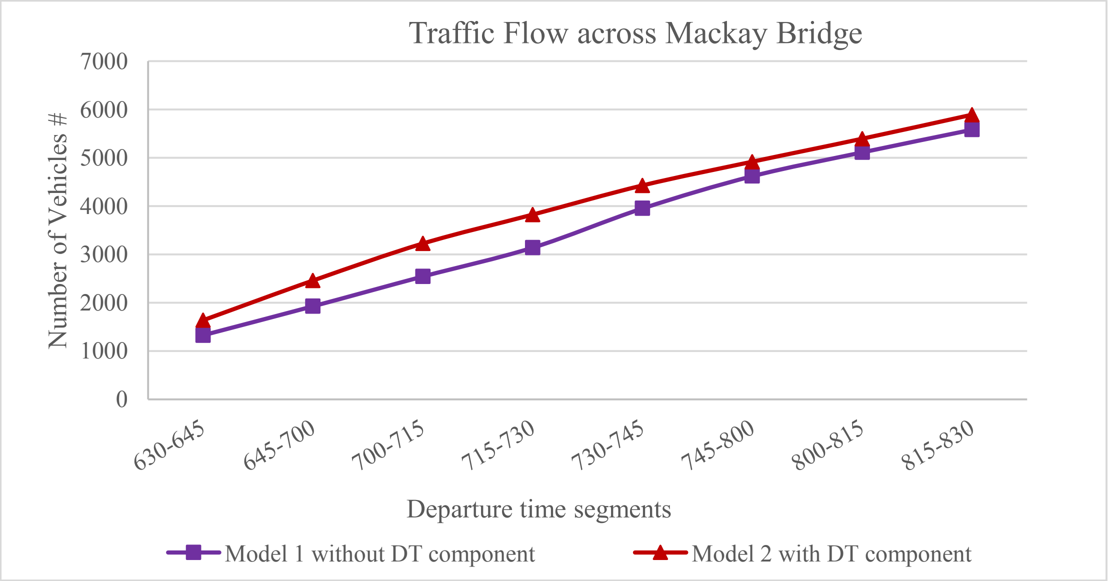

Figure 4-8 Cumulative Traffic Flow across the Mackay Bridge

4.6 Summary

This chapter presents a framework that proposes a CPT-based departure time choice model for dynamic traffic microsimulation. The proposed framework is an improvement of the existing microscopic traffic models. Traditional simulation models lack departure time choice modelling component that can incorporates travellers' adjustment of the departure time.

The proposed framework is applied to a case study in Halifax, Canada. The application demonstrated the potential efficacy of the proposed framework in predicting driver's responses to a sudden bridge closure incident. The cumulative prospect theory-based model recognizes that drivers adjust their departure time based on their previous experience and optimize the choices to avoid very early departure from home/very early arrival at work. Model 2 with the DT component predicts increments in travel demand and average traffic delay in the network. The results suggest that individuals shift to earlier departure time segments to accommodate the anticipated delays in the network. As the number of the arrived vehicles remains same, additional 5235 vehicles are added to the traffic volume obtained from model 1 without the DT component. The importance of such an explicit departure time choice component becomes more evident from the analysis of the local traffic impacts due to the closure of the bridge. However, local traffic conditions improve if drivers adjust their departure time to avoid late arrival. Moreover, a preliminary investigation suggests that the model 2 with the DT component estimates an additional traffic delay cost in the amount of \$7,970 (942 hours * \$8.46/hour~\$7970) with respect to model 1 without the DT component by considering value of travel time (VOT) for the Halifax residents as \$8.46 *(Habib and Richardson, 2012).* It can be asserted from the results that the proposed framework improves the estimation of traffic impacts by incorporating the departure time choice decision within dynamic microsimulation model.

The novelty of the proposed framework is that it captures the differential responses of the travellers to the sudden risk events to estimate the traffic flow in the stochastic network. Future research should include the development of a CPT-based route choice model combining with a CPT-based departure time choice model in a single dynamic microsimulation framework.

Nevertheless, this research contributes significantly by offering a comprehensive framework of DTA modelling with an explicit CPT-based departure time choice component. The framework improves the estimation of the Measures of Effectiveness (MOEs) and could be useful for policy testing, particularly, in developing risk management strategies. Since the re-decking will be continuing further, the study could provide decision makers' insights into contingencies and mitigation planning to minimize the potential impacts on daily activities.

Chapter 5

Conclusion

5.1 Summary of the Chapters

This thesis presented a comprehensive framework of dynamic microsimulation modelling which is capable of taking into account the drivers' departure time and route choices in response to any sudden risk event in the stochastic transport network.

This study applied the proposed framework to a case study of transportation system's critical infrastructure renewal in Halifax, Canada that poses considerable risks of disruption to the network during the morning rush hour. Initially, the study investigated the risks associated with the project to inform the scenario building process for traffic impact assessment within a microscopic traffic simulation framework. The risk results suggest that the bridge opening delay could be 22 minutes, 1.5 hours, and 2.6 hours for low, medium, and high consequences respectively. The results inform that bridge opening delay could range from 18% to 30% for an hour, 25% to 45% for 1 to 2-hour period, and 20% to 40% for 2 to 3-hour period. An hourly interval of delay scenario is then considered for parsimony and consistent evaluation of traffic impacts. The scenarios include (1) 1-hour delay, (2) 2-hour delay, and (3) 3-hour delay in re-opening of the bridge in the morning.

The network impact analysis suggests that the increment in number of operating vehicles becomes steady at 30% suggesting that the network has reached its capacity after 2-hour closure of the bridge. The results also reveal that any delay over 2 hours in bridge opening would add slight change to the impacts on the network. However, the initial effort made some pre-determined assumptions for testing the risk scenario within the microsimulation model. Particularly, the route choice behaviour was not stochastic in this static assignment-based microsimulation model.

Next, the study enhances the model by developing a dynamic traffic assignment (DTA)-based microsimulation model, which takes into account driver's route choice behaviour. The DTA-based model improves the estimation of the traffic impacts by capturing the congestion spillback in the network. For instance, traffic flow across the Mackay Bridge declines after 8:00 am due to the appearance of the spill over, originated at the Windsor Street Exchange, the busiest intersection located downstream of the bridge. Although the DTA-based model captures the driver's stochastic behaviour; however, it lacks a departure time choice component that can account the driver's adjustment of the departure time. The major contribution of this thesis is that it developed a **Cumulative Prospect Theory (CPT)**-based departure time choice model for dynamic traffic microsimulation. The novelty of the proposed framework is that it can model the asymmetric responses of the travellers towards the changes in traffic network performances. The DTA-based simulation model with the DT component reports that both the operational as well as the discharge capacity of the network are utilized during the closure of the MacDonald Bridge. The results suggest that travel demand increases by 5235 vehicles after the inclusion of the departure time choice component into the simulation system. However, the arrival rate remains equal in both the simulation models; with and without the DT component. In consequence, total traffic delay increases by 942 hours with respect to the model without the DT component. Hence, model 1 may underestimate the traffic delay in the absence of a DT component during traffic flow analysis. On the other hand, the model with the DT component reveals that traffic condition improves at local network. The reason is that the proposed framework allows for optimal routing policies and proper departure time planning in the context of sudden interruption in the network.

This study assumed the values for β and δ as 0.88 and 0.69 respectively. Future research endeavour should develop experimental design to estimate these values for Halifax. The proposed framework in this thesis is applied only for peak hour traffic impact assessment. Further study should focus on developing a traffic simulation model for 24-hour traffic impact study. Moreover, the degree of being the model close to the reality needs also to be validated with observed data during disruptions. In addition, future efforts should be invested in combining the developed CPT-based departure time choice model with a CPT-based route choice model within a single traffic microsimulation framework.

5.2 Practical Implication of the Results

There are several practical implications of the results presented in this thesis. This study performed a traffic delay cost analysis for the period of 6:30 am – 8:30 am during the closure of the MacDonald Bridge. The proposed model with the DT component predicted that traffic delay increases by 2094-hour with respect to no bridge closure scenario. No bridge closure scenario has been tested within the DTA-based microsimulation model *(Alam and Habib, 2016)*. This traffic delays could incur an economic loss of $17,700 (2094 hours*$8.46/hour~ $17700) on road users within that two hours during the closure of the bridge. The economic loss could be more significant for longer time closure of the bridge. Therefore, appropriate traffic operation and traffic demand management (TDM) policy should be in place to mitigate the traffic impacts as well as the economic losses on road users during making trips in the network. This thesis offers many results that give insights into developing contingencies and mitigation strategies aiming to increasing the efficiency of the network during the bridge closure period. For instance, the spillover resulted from the queue propagation at Windsor Street Exchange intersection was evident across the Mackay Bridge and its surrounding area (i.e. Victoria Rd and Highway 111). A policy that prioritizes the traffic flow from the Mackay Bridge could be adopted to discharge the traffic volume quickly from the Mackay Bridge (see Appendix A12)

Moreover, traffic can be diverted towards Victoria Rd and Burnside Drive before entering the Mackay Bridge to take the Highway 102 rather than taking the Mackay Bridge (see Appendix A13). An access management strategy could also help to dissipate the queue along the Highway 111 for instance, toll protocol of the Mackay Bridge could be removed during the closure of the MacDonald Bridge (see Appendix 14)

The proposed model implies that few upstream locations along Highway 111 anticipates a little change in traffic flow with respect to no bridge closure scenario. The results highlight the existence of adaptive capacity at those locations. These locations are close to Waverly Rd, Main Street and Portland Street. Therefore, these streets could be the potential locations for placing the Variable Message Sign (VMS) to guide the driver upfront for an optimal routing during the closure of the bridge (see Appendix A13).

Moreover, emerging technologies including, Information and Communication Technologies (ICT), Facebook, Twitter could also be useful to update the driver about en-route traffic condition in the network.

This thesis also evaluated overall network performances and concluded that 2-hour closure of the bridge causes major disruption to the network. A tolerance period might be designed from this result to quickly take necessary ground steps before the network becomes saturated during the closure incident.

Traffic demand management policies could be developed to reduce or re-distribute the travel demand in the network. For example, the business establishments could be encouraged to arrange flexible work hour for their employee, allow them to work at home during the closure of the MacDonald Bridge. Transit ridership could also be promoted to reduce the traffic in the network. Strategies for instance, free ferry pass could be provided to the road users to promote the transit ridership on the day of the bridge closure.

Furthermore, this thesis offers results and discussions that can help us for proactive risk governance for the re-decking of the Mackay Bridge which is going to start in 2023.

5.3 Major Contributions

This thesis contributes significantly in the field of dynamic traffic microsimulation modelling for traffic impact assessment during sudden risk occurrence in the network. This study develops a sequential modelling framework that combines risk assessment with microsimulation modelling. The proposed microsimulation modelling framework is capable of capturing the driver's stochastic behaviour including, re-routing during the sudden interruption in the network. The major contribution of the thesis is that it enhances the dynamic traffic microsimulation modelling by incorporating a CPT-based departure time choice component within the system that can capture driver's differential responses to the risk events in the network. The proposed framework demonstrates an improvement in estimation of the traffic impact by considering both the driver's departure time and routing decision under risk. This model could be a decision support tool during emergencies for instance, emergency evacuation of Halifax peninsula. The model could be an asset during the evaluation of the large transportation infrastructure development project and its impacts on surrounding network in future for instance, the Mackay Bridge re-decking in 2023.

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Appendix A1: Average Wind Speed and Standard Deviation in Fall, 2014, and General Threshold Values for Weather Factors

Months	Average Wind Speed (km/hr.)	Standard Deviation (km/hr.)
September	15.71	7.38
October	18.43	7.83
November	19.16	9.21
December	19.88	10.32

Threshold values of the factors (*Xie et al., 2005*) that provide insights into classification of the factors and consequences

Wind

Threshold Values

1. Wind speed of 32.2 km/hr. reduces the productivity by 30%-40%
2. Wind speed above 55 km/hr. implies a non-work day

*Classification*s *Used*

1. Low wind speed: 0-30 km/hr.
2. Medium wind speed: 30-55 km/hr.
3. High wind speed: > 55 km/hr.

Temperature

Threshold Values

1. At 4.44 ° C- productivity is 90%
2. At -40 ° C- productivity is 20%

Classifications Used

1. Low temperature: -40 to -20 ° C
2. Medium wind speed: -20-0 ° C
3. High wind speed: > 0 ° C

Precipitation

Threshold Values

3. Precipitation within 6.3 mm – 12.7 mm has significant effects on construction like paving, foundation etc.

Classifications Used

1. Low precipitation: 0-20 mm
2. Medium precipitation: 20-40 mm
3. High precipitation: > 40 mm

Appendix A2: Fuzzy Relation Matrix $M\ (F, C)$ for Case 1

Wind

Low Frequency-Low Consequence

	0.0	0.1	0.2	0.3	0.4
0.0	1.0	1.0	0.71	0.43	0.14
0.1	1.0	1.0	0.71	0.43	0.14
0.2	1.0	1.0	0.71	0.43	0.14
0.3	1.0	1.0	0.71	0.43	0.14
0.4	0.84	0.84	0.71	0.43	0.14
0.5	0.69	0.69	0.69	0.43	0.14
0.6	0.53	0.53	0.53	0.43	0.14
0.7	0.38	0.38	0.38	0.38	0.14
0.8	0.22	0.22	0.22	0.22	0.14
0.9	0.06	0.06	0.06	0.06	0.06

Medium Frequency-Low Consequence

	0.0	0.1	0.2	0.3	0.4
0.3	0.1	0.1	0.2	0.3	0.4
0.4	0.16	0.16	0.16	0.16	0.14
0.5	0.31	0.31	0.31	0.31	0.14
0.6	0.47	0.47	0.47	0.43	0.14
0.7	0.63	0.63	0.63	0.43	0.14
0.8	0.78	0.78	0.71	0.43	0.14
0.9	0.94	0.94	0.71	0.43	0.14

High Frequency-Low Consequence

	0.0	0.1	0.2	0.3	0.4
1.0	1.0	1.0	0.71	0.43	0.14

Temperature

Low Frequency-Low Consequence

	0.0	0.1	0.2	0.3	0.4
0.0	1.0	1.0	0.71	0.43	0.14
0.1	1.0	1.0	0.71	0.43	0.14

Medium Frequency-Low Consequence

	0.0	0.1	0.2	0.3	0.4
0.1	0.57	0.57	0.57	0.43	0.14
0.2	0.96	0.96	0.71	0.43	0.14
0.3	0.81	0.81	0.71	0.43	0.14
0.4	0.67	0.67	0.67	0.43	0.14
0.5	0.52	0.52	0.52	0.43	0.14
0.6	0.37	0.37	0.37	0.37	0.14
0.7	0.22	0.22	0.22	0.22	0.14
0.8	0.07	0.07	0.07	0.07	0.07

High Frequency-Low Consequence

	0.0	0.1	0.2	0.3	0.4
0.3	0.19	0.19	0.19	0.19	0.14
0.4	0.33	0.33	0.33	0.33	0.14
0.5	0.48	0.48	0.48	0.43	0.14
0.6	0.63	0.63	0.63	0.43	0.14
0.7	0.78	0.71	0.71	0.43	0.14
0.8	0.93	0.93	0.71	0.43	0.14
0.9	1.0	1.0	0.71	0.43	0.14
1.0	1.0	1.0	0.71	0.43	0.14

Precipitation

Low Frequency-Low Consequence

	0.0	0.1	0.2	0.3	0.4
0.0	1.0	1.0	0.71	0.43	0.14
0.1	1.0	1.0	0.71	0.43	0.14
0.2	1.0	1.0	0.71	0.43	0.14
0.3	1.0	1.0	0.71	0.43	0.14
0.4	0.83	0.83	0.71	0.43	0.14
0.5	0.67	0.67	0.67	0.43	0.14
0.6	0.5	0.5	0.5	.43	0.14
0.7	0.33	0.33	0.33	0.33	0.14
0.8	0.17	0.17	0.17	0.17	0.14

Medium Frequency-Low Consequence

	0.0	0.1	0.2	0.3	0.4
0.4	0.17	0.17	0.17	0.17	0.14
0.5	0.33	0.33	0.33	0.33	0.14
0.6	0.5	0.5	0.5	0.43	0.14
0.7	0.67	0.67	0.67	0.43	0.14
0.8	0.83	0.83	0.71	0.43	0.14
0.9	1.0	1.0	0.71	0.43	0.14

High Frequency-Low Consequence

	0.0	0.1	0.2	0.3	0.4
1.0	1.0	1.0	0.71	0.43	0.14

Bridge Construction Incident

Low Frequency-Low Consequence

	0.0	0.1	0.2	0.3	0.4
0.0	1.0	1.0	0.71	0.43	0.14
0.1	1.0	1.0	0.71	0.43	0.14
0.2	1.0	1.0	0.71	0.43	0.14
0.3	1.0	1.0	0.71	0.43	0.14
0.4	0.78	0.78	0.71	0.43	0.14
0.5	0.56	0.56	0.56	0.43	0.14
0.6	0.33	0.33	0.33	0.33	0.14
0.7	0.11	0.11	0.11	0.11	0.11

Medium Frequency-Low Consequence

	0.0	0.1	0.2	0.3	0.4
0.3	1.0	1.0	0.71	0.43	0.14
0.4	0.22	0.22	0.22	0.22	0.14
0.5	0.44	0.44	0.44	0.43	0.14
0.6	0.67	0.67	0.67	0.43	0.14
0.7	0.89	0.89	0.71	0.43	0.14
0.8	0.75	0.75	0.71	0.43	0.14

High Frequency-Low Consequence

	0.0	0.1	0.2	0.3	0.4
0.8	0.25	0.25	0.25	0.25	0.14
0.9	0.75	0.75	0.71	0.43	0.14
1.0	1.0	1.0	0.71	0.43	0.14

Appendix A3: Fuzzy Relation Matrix $N(C, D)$ for Case 1

Low Consequence-Low Delay

	0.0	0.5	1.0
0.0	1.0	0.8	0.4
0.1	1.0	0.8	0.4
0.2	0.71	0.71	0.4
0.3	0.43	0.43	0.4
0.4	0.14	0.14	0.14

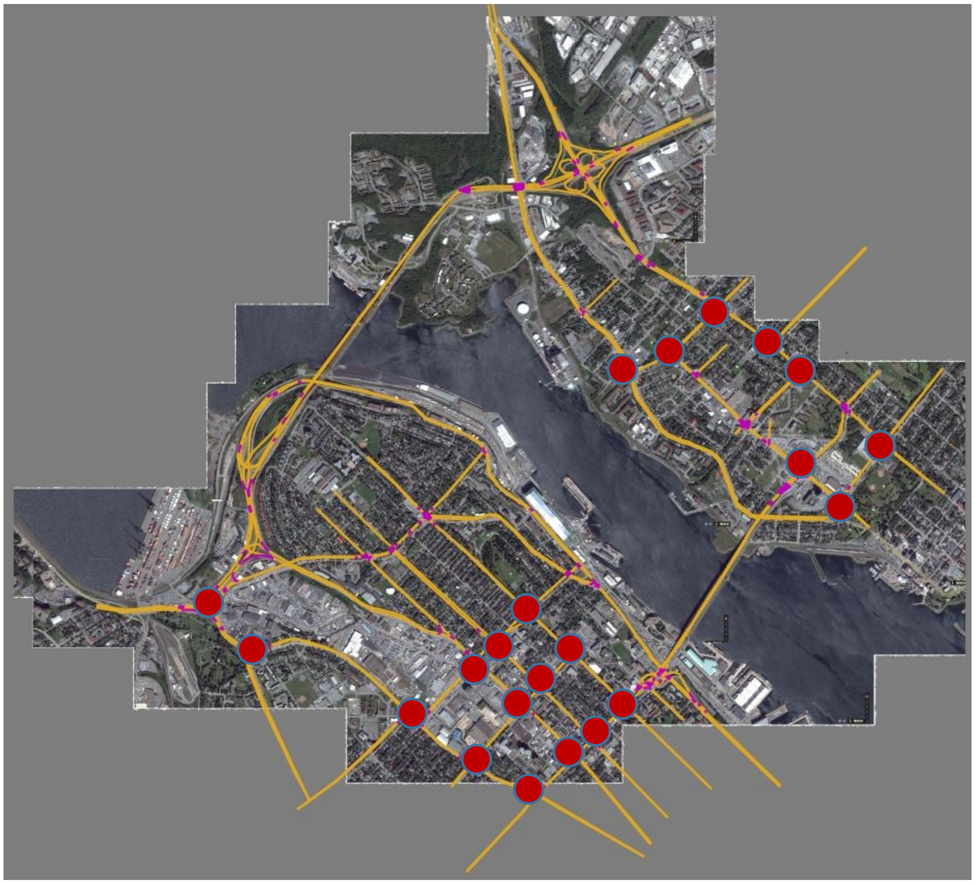
Medium Consequence-Low Delay

	0.0	0.5	1.0
0.2	0.29	0.29	0.29
0.3	0.57	0.57	0.4
0.4	0.86	0.8	0.4
0.5	0.88	0.8	0.4
0.6	0.63	0.63	0.4
0.7	0.38	0.38	0.38
0.8	0.13	0.13	0.13

High Consequence-Low Delay

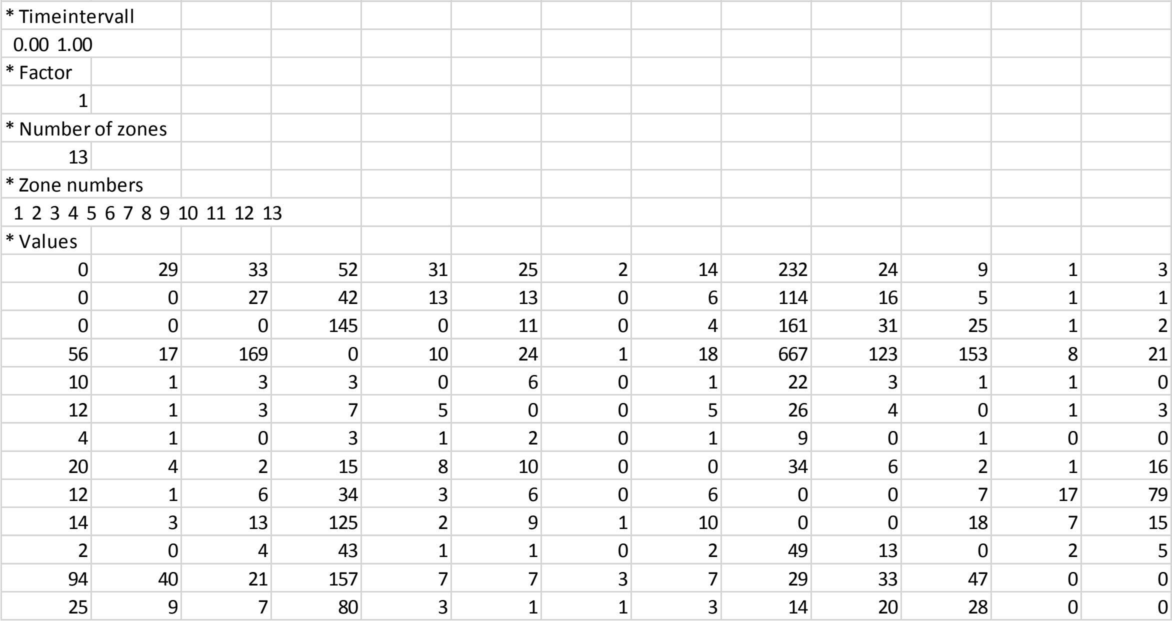
	0.0	0.5	1.0
0.8	0.67	0.67	0.4
0.9	1.0	0.8	0.4
1.0	1.0	0.8	0.4

Appendix A4: Selected Locations for Validations



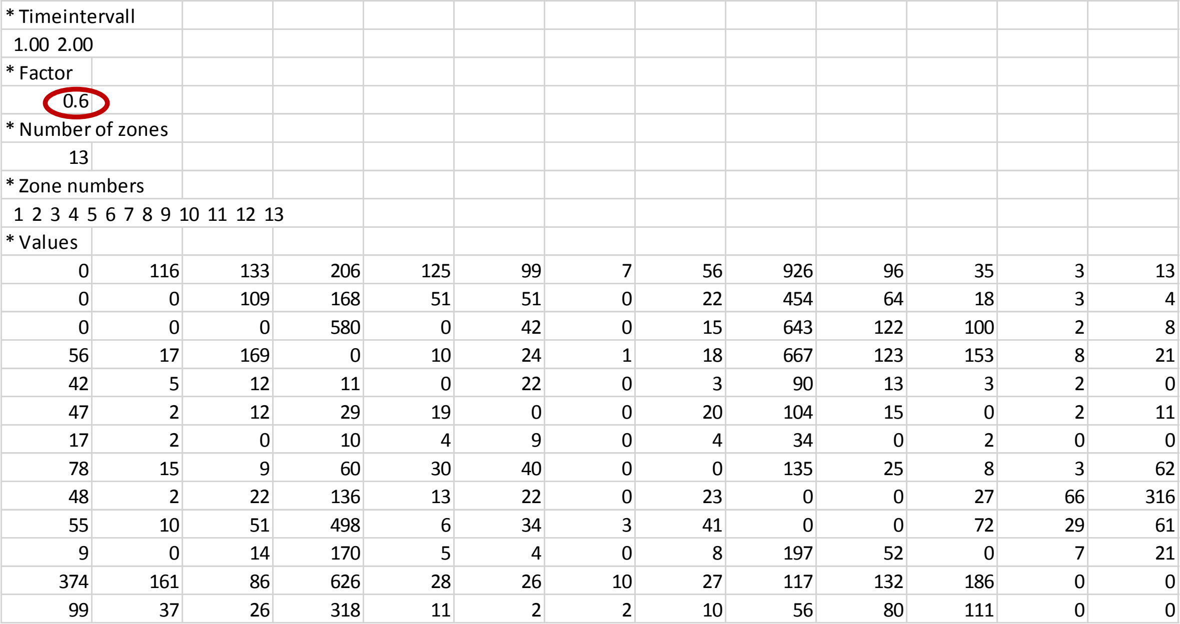
Appendix A5: Origin-destination (OD) Matrix

(i) OD Matrix (5:30 am – 6:30 am)



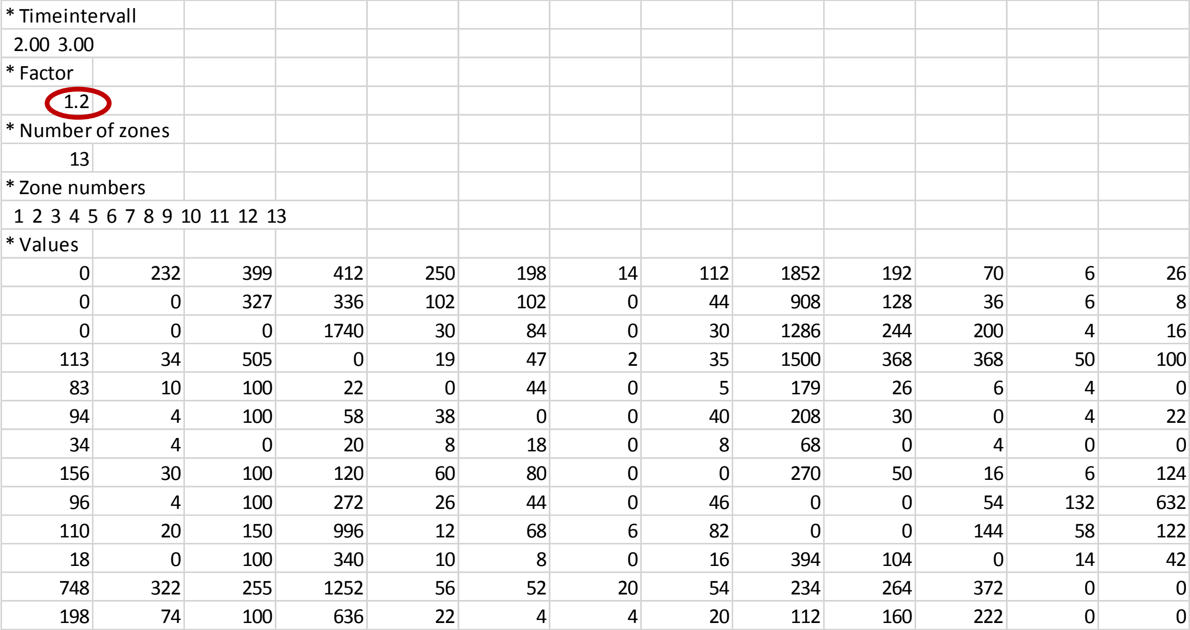
* Timeintervall												
0.00 1.00												
* Factor												
1												
* Number of zones												
13												
* Zone numbers												
1 2 3 4 5 6 7 8 9 10 11 12 13												
* Values												
0	29	33	52	31	25	2	14	232	24	9	1	3
0	0	27	42	13	13	0	6	114	16	5	1	1
0	0	0	145	0	11	0	4	161	31	25	1	2
56	17	169	0	10	24	1	18	667	123	153	8	21
10	1	3	3	0	6	0	1	22	3	1	1	0
12	1	3	7	5	0	0	5	26	4	0	1	3
4	1	0	3	1	2	0	1	9	0	1	0	0
20	4	2	15	8	10	0	0	34	6	2	1	16
12	1	6	34	3	6	0	6	0	0	7	17	79
14	3	13	125	2	9	1	10	0	0	18	7	15
2	0	4	43	1	1	0	2	49	13	0	2	5
94	40	21	157	7	7	3	7	29	33	47	0	0
25	9	7	80	3	1	1	3	14	20	28	0	0

(ii) OD Matrix (6:30 am – 7:30 am)



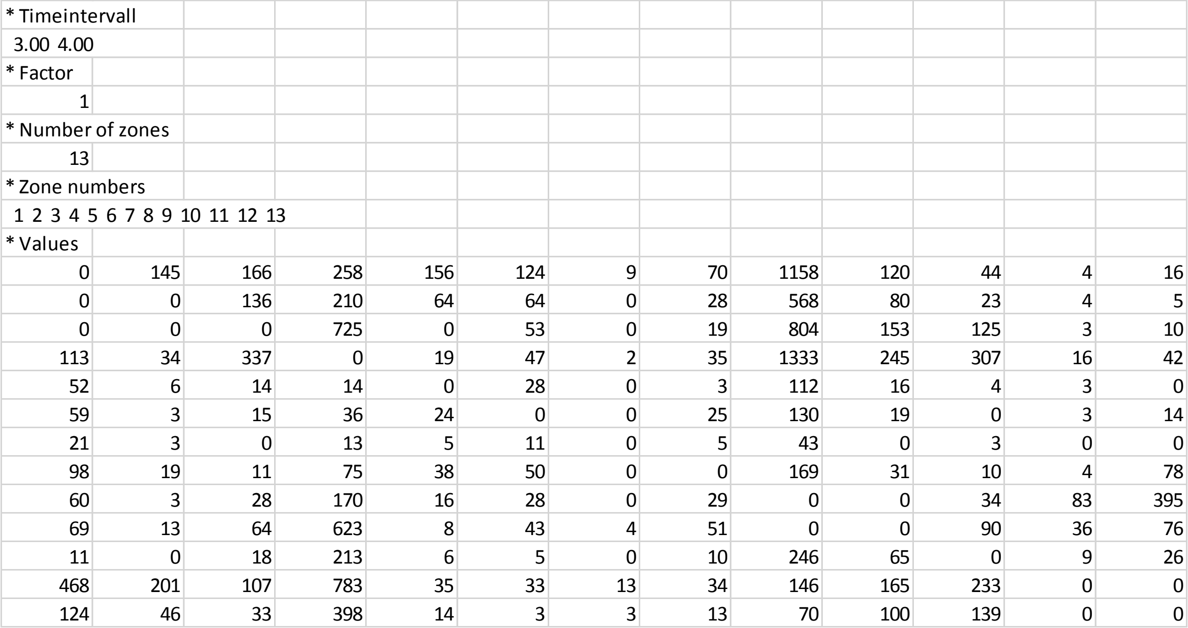
* Timeintervall												
1.00 2.00												
* Factor												
0.6												
* Number of zones												
13												
* Zone numbers												
1 2 3 4 5 6 7 8 9 10 11 12 13												
* Values												
0	116	133	206	125	99	7	56	926	96	35	3	13
0	0	109	168	51	51	0	22	454	64	18	3	4
0	0	0	580	0	42	0	15	643	122	100	2	8
56	17	169	0	10	24	1	18	667	123	153	8	21
42	5	12	11	0	22	0	3	90	13	3	2	0
47	2	12	29	19	0	0	20	104	15	0	2	11
17	2	0	10	4	9	0	4	34	0	2	0	0
78	15	9	60	30	40	0	0	135	25	8	3	62
48	2	22	136	13	22	0	23	0	0	27	66	316
55	10	51	498	6	34	3	41	0	0	72	29	61
9	0	14	170	5	4	0	8	197	52	0	7	21
374	161	86	626	28	26	10	27	117	132	186	0	0
99	37	26	318	11	2	2	10	56	80	111	0	0

(iii) OD Matrix (7:30 am – 8:30 am)



* Timeintervall												
2.00 3.00												
* Factor												
1.2												
* Number of zones												
13												
* Zone numbers												
1 2 3 4 5 6 7 8 9 10 11 12 13												
* Values												
0	232	399	412	250	198	14	112	1852	192	70	6	26
0	0	327	336	102	102	0	44	908	128	36	6	8
0	0	0	1740	30	84	0	30	1286	244	200	4	16
113	34	505	0	19	47	2	35	1500	368	368	50	100
83	10	100	22	0	44	0	5	179	26	6	4	0
94	4	100	58	38	0	0	40	208	30	0	4	22
34	4	0	20	8	18	0	8	68	0	4	0	0
156	30	100	120	60	80	0	0	270	50	16	6	124
96	4	100	272	26	44	0	46	0	0	54	132	632
110	20	150	996	12	68	6	82	0	0	144	58	122
18	0	100	340	10	8	0	16	394	104	0	14	42
748	322	255	1252	56	52	20	54	234	264	372	0	0
198	74	100	636	22	4	4	20	112	160	222	0	0

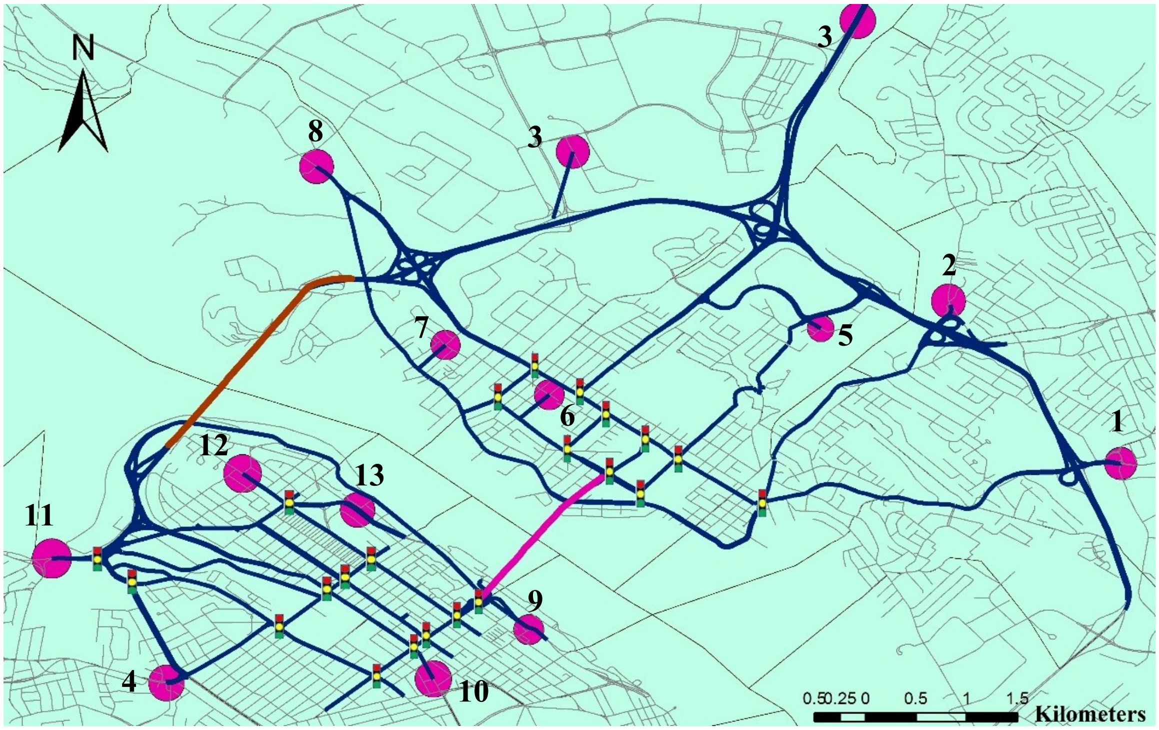
(iv) OD Matrix (8:30 am – 9:30 am)



* Timeintervall												
3.00 4.00												
* Factor												
1												
* Number of zones												
13												
* Zone numbers												
1 2 3 4 5 6 7 8 9 10 11 12 13												
* Values												
0	145	166	258	156	124	9	70	1158	120	44	4	16
0	0	136	210	64	64	0	28	568	80	23	4	5
0	0	0	725	0	53	0	19	804	153	125	3	10
113	34	337	0	19	47	2	35	1333	245	307	16	42
52	6	14	14	0	28	0	3	112	16	4	3	0
59	3	15	36	24	0	0	25	130	19	0	3	14
21	3	0	13	5	11	0	5	43	0	3	0	0
98	19	11	75	38	50	0	0	169	31	10	4	78
60	3	28	170	16	28	0	29	0	0	34	83	395
69	13	64	623	8	43	4	51	0	0	90	36	76
11	0	18	213	6	5	0	10	246	65	0	9	26
468	201	107	783	35	33	13	34	146	165	233	0	0
124	46	33	398	14	3	3	13	70	100	139	0	0

Appendix A6: Super Loading Zones

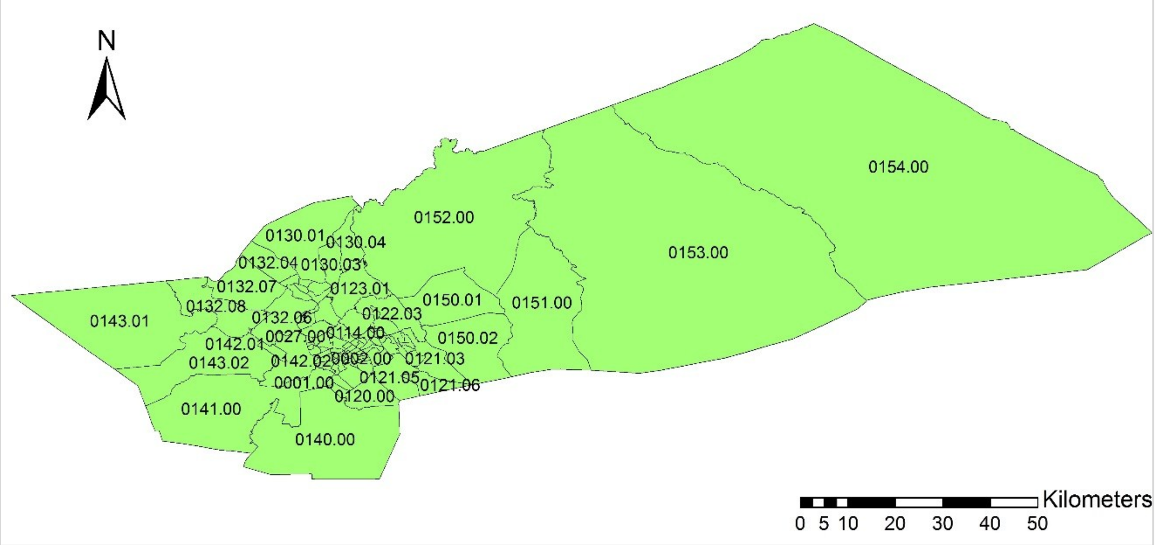
(i) An Illustration of Super Loading Zones in Traffic Microsimulation Model



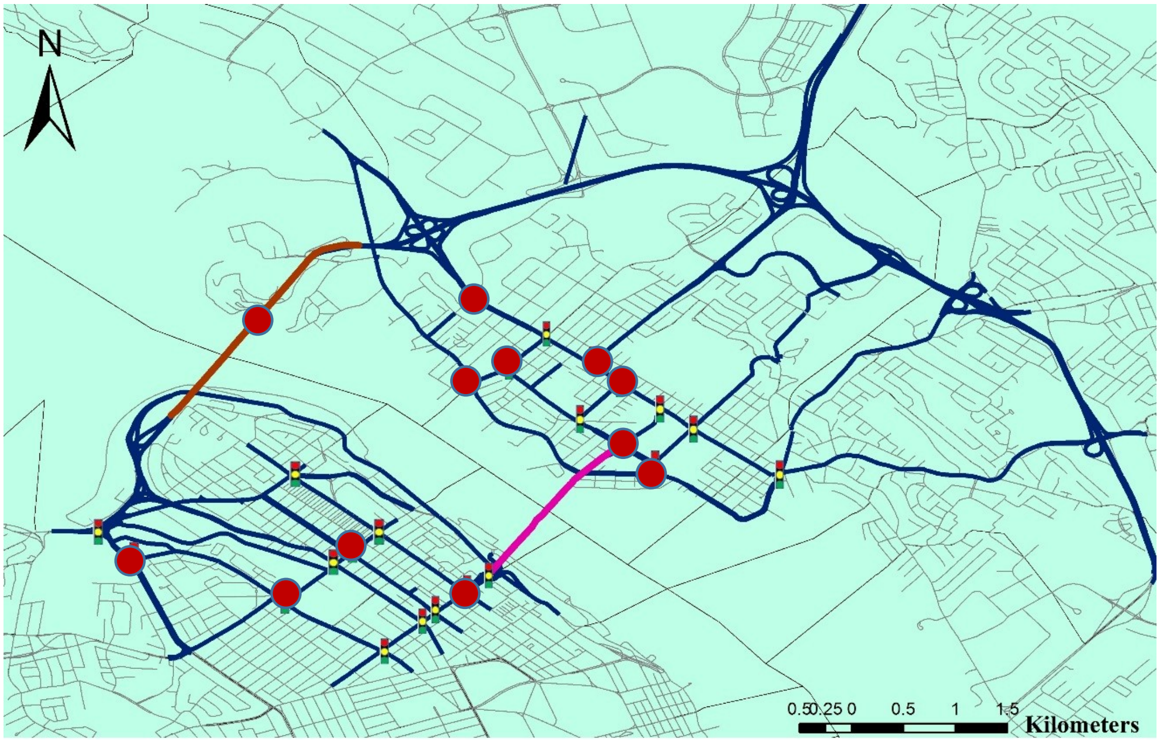
(ii) Thirteen Super Loading Zones Out of Eighty-Seven Zones

Super Loading Zone #	**Aggregated Zones**	**Total**
1	100-103, 104.01, 104.02, 120, 121.02-121.08, 122.01, 122.02, 150.02	16
2	105.01, 105.02, 106.01, 106.02, 107, 122.03, 150.01, 151, 153, 154	10
3	123.01, 130.01, 130.02, 152	4
4	17, 18, 19, 23-25, 26.01, 26.02, 131.01-131.05, 132.03-132.06, 140, 142.01, 142.02, 143.01, 143.02	22
5	108, 109	2
6	110, 111	2
7	112	1
8	113, 114, 123.08	3
9	3, 4, 7-10	6
10	1, 2, 5, 6, 11-16	10
11	25.01-25.03, 26.02, 27, 123.04-123.06	8
12	22	1
13	20, 21	2
Total		**87**

(iii) An Illustration of Eighty-seven Zones

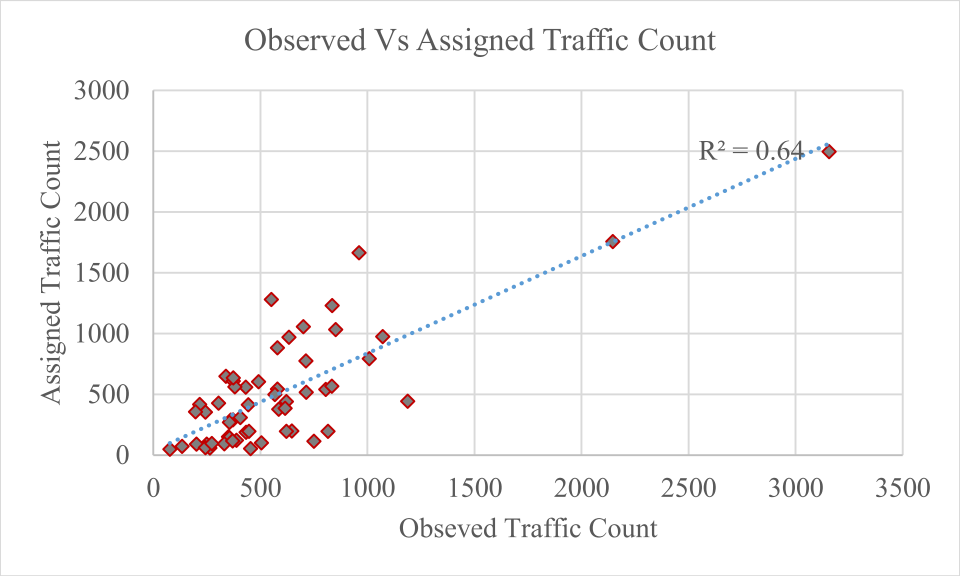


Appendix A7: Selected Locations for Validations

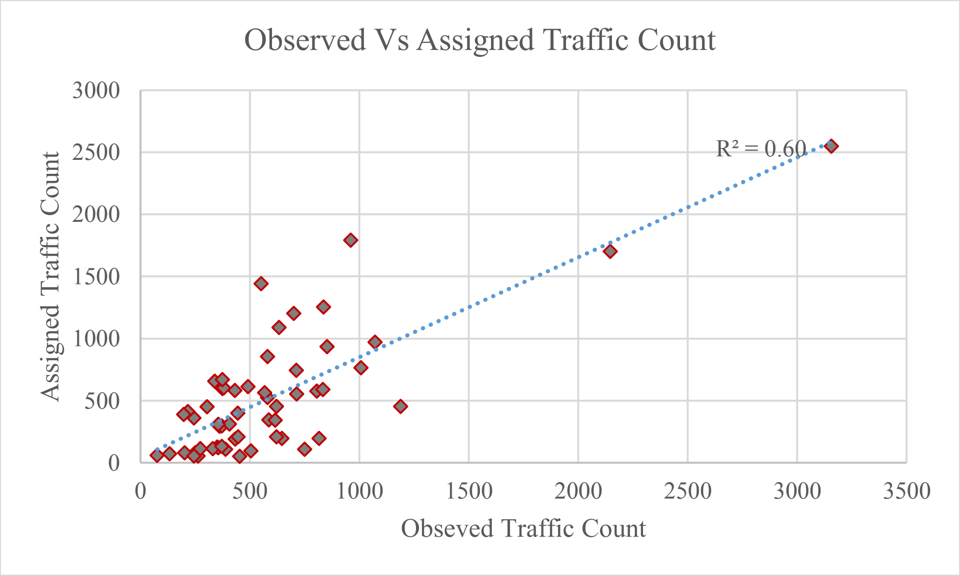


Appendix A8: Validation Results after Calibration of the DTA-based Microsimulation Model

(i) Validation Results for Driving Behaviour Parameter Set 5

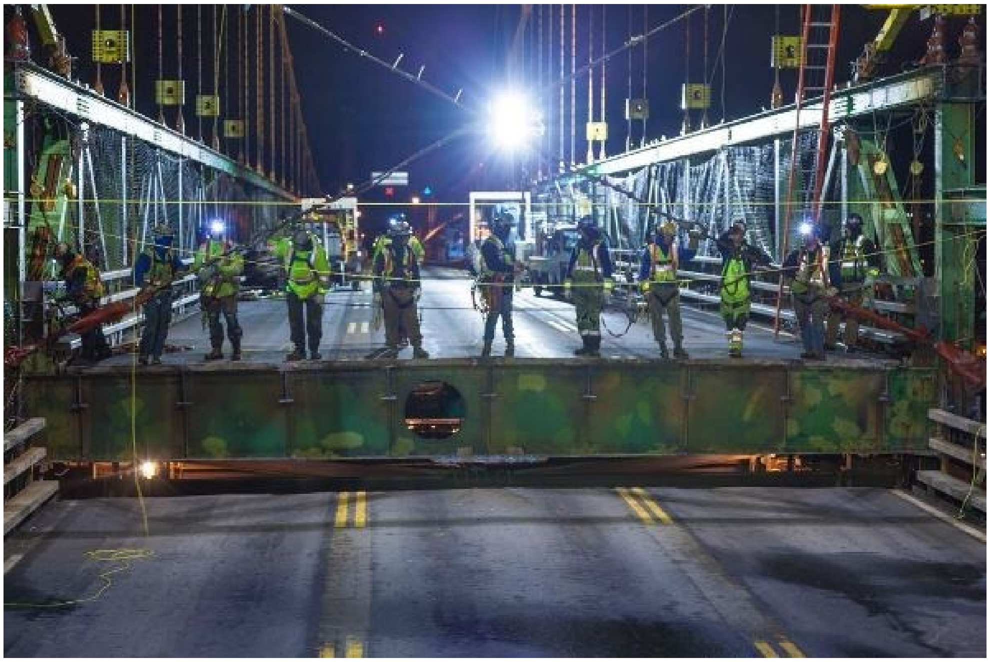


(ii) Validation Results for Driving Behaviour Parameter Set 6



Appendix 9: Re-decking Activities and Traffic Impacts during Big Lift Project

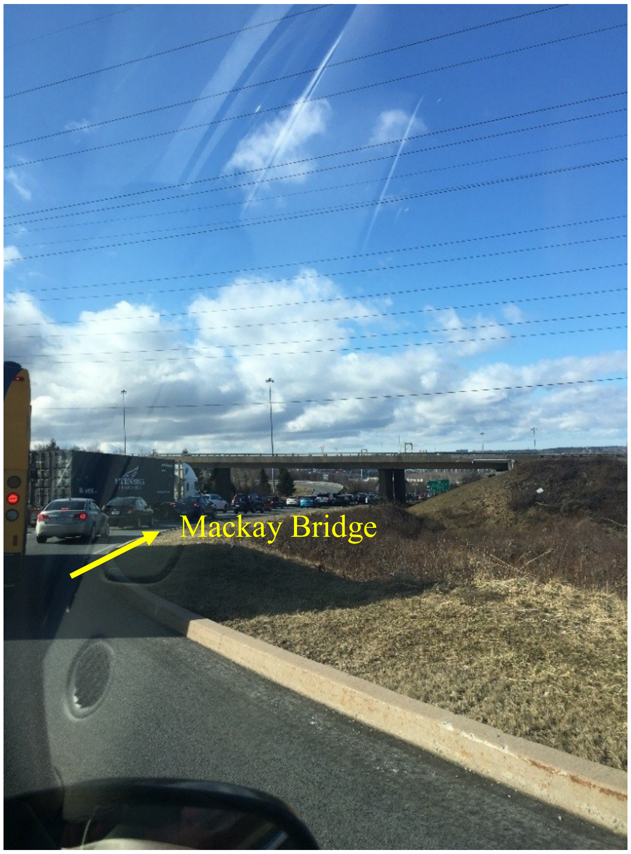
(i) Re-decking of the MacDonald Bridge



(Source:https://www.instagram.com/p/BFjsxuyHlpa/?taken-by=biglifthfx)

(ii) Traffic Queue along Highway 111 Moving to the Mackay Bridge during the Closure of the Macdonald Bridge

(iii) Traffic Queue on the Mackay Bridge Ramp during the Closure of the MacDonald Bridge



(iv) Traffic Queue before the Toll Section of the Mackay Bridge during the Closure of the MacDonald Bridge

Appendix A10: Departure Time Segments, Travel Time Losses, and Associated Probabilities

(i) OD Pair: 1-9

6:30 am – 7:30 am				
Departure time segments, d_i	**Segment d₁ (6:30 am – 6:45 am)**	**Segment d₂ (6:45 am – 7:00 am)**	**Segment d₃ (7:00 am – 7:15 am)**	**Segment d₄ (7:15 am – 7:30 am)**
Travel time losses, x_q (min)	12	12	8	8
Probability, p_q	0.49	0.40	0.89	0.89

7:30 am -8:30 am				
Departure time segments, d_i	**Segment d₅ (7:30 am – 7:45 am)**	**Segment d₆ (7:45 am – 8:00 am)**	**Segment d₇ (8:00 am – 8:15 am)**	**Segment d₈ (8:15 am – 8:30 am)**
Travel time losses, x_q (min)	24	32	36	36
Probability, p_q	0.59	0.66	0.39	0.39

(ii) OD Pair: 1-10

6:30 am – 7:30 am				
Departure time segments, d_i	**Segment d₁ (6:30 am – 6:45 am)**	**Segment d₂ (6:45 am – 7:00 am)**	**Segment d₃ (7:00 am – 7:15 am)**	**Segment d₄ (7:15 am – 7:30 am)**
Travel time losses, x_q (min)	12	12	8	8
Probability, p_q	0.29	0.33	0.82	0.82

7:30 am -8:30 am				
Departure time segments, d_i	**Segment d₅ (7:30 am – 7:45 am)**	**Segment d₆ (7:45 am – 8:00 am)**	**Segment d₇ (8:00 am – 8:15 am)**	**Segment d₈ (8:15 am – 8:30 am)**
Travel time losses, x_q (min)	28	32	36	36
Probability, p_q	0.52	0.78	0.52	0.52

(iii) OD Pair: 1-11

6:30 am – 7:30 am				
Departure time segments, d_i	**Segment d_1 (6:30 am – 6:45 am)**	**Segment d_2 (6:45 am – 7:00 am)**	**Segment d_3 (7:00 am – 7:15 am)**	**Segment d_4 (7:15 am – 7:30 am)**
Travel time losses, x_q (min)	4	4	8	8
Probability, p_q	1.0	0.63	1.0	1.0

7:30 am -8:30 am				
Departure time segments, d_i	**Segment d_5 (7:30 am – 7:45 am)**	**Segment d_6 (7:45 am – 8:00 am)**	**Segment d_7 (8:00 am – 8:15 am)**	**Segment d_8 (8:15 am – 8:30 am)**
Travel time losses, x_q (min)	24	32	40	40
Probability, p_q	0.67	1.0	0.36	0.36

Appendix A11: Departure Time Choice Set, Prospects and CPT Utilities for OD Pairs

(i) OD Pair: 1-9

Choices	Prospects (x_q, p_q)	CPT Utility (CWV)	Choices	Prospects (x_q, p_q)	CPT Utility (CWV)
d_2 to d_1	(-12, .20)	-2.27	d_5 to d_4	(-8, .52)	-2.94
d_3 to d_1	(-12, .44)	-3.7	d_6 to d_3	(-8, .74)	-3.19
d_3 to d_2	(-12, .36)	-3.25	d_6 to d_4	(-8, .74)	-3.19
d_4 to d_1	(-12, .44)	-3.7	d_6 to d_5	(-24, .43)	-6.32
d_4 to d_2	(-12, .36)	-3.25	d_7 to d_4	(-8, .38)	-2.24
d_4 to d_3	(-8, .79)	-4.14	d_7 to d_5	(-24, .22)	-4.59
d_5 to d_2	(-12, .24)	-2.54	d_7 to d_6	(-32, .31)	-6.32
d_5 to d_3	(-8, .53)	-2.94			

(ii) OD Pair: 1-10

Choices	Prospects (x_q, p_q)	CPT Utility (CWV)	Choices	Prospects (x_q, p_q)	CPT Utility (CWV)
d_2 to d_1	(-12, .10)	-1.49	d_5 to d_4	(-8, .43)	-2.55
d_3 to d_1	(-12, .24)	-2.55	d_6 to d_3	(-8, .64)	-3.41
d_3 to d_2	(-12, .27)	-2.75	d_6 to d_4	(-8, .64)	-3.41
d_4 to d_1	(-12, .24)	-2.55	d_6 to d_5	(-28, .41)	-7.43
d_4 to d_2	(-12, .27)	-2.75	d_7 to d_4	(-8, .43)	-2.55
d_4 to d_3	(-8, .67)	-3.55	d_7 to d_5	(-28, .27)	-5.79
d_5 to d_2	(-12, .17)	-2.1	d_7 to d_6	(-32, .41)	-8.35
d_5 to d_3	(-8, .43)	-2.55			

(iii) OD Pair: 1-11

Choices	Prospects (x_q, p_q)	CPT Utility (CWV)	Choices	Prospects (x_q, p_q)	CPT Utility (CWV)
d_2 to d_1	(-4, .63)	-1.83	d_5 to d_4	(-8, 67)	-3.54
d_3 to d_1	(-4, 1.0)	-3.4	d_6 to d_3	(-8, 1.0)	-6.24
d_3 to d_2	(-4, .63)	-1.83	d_6 to d_4	(-8, 1.0)	-6.24
d_4 to d_1	(-4, 1.0)	-3.4	d_6 to d_5	(-24, .67)	-9.29
d_4 to d_2	(-4, .63)	-1.83	d_7 to d_4	(-8, .36)	-2.29
d_4 to d_3	(-8, 1.0)	-6.24	d_7 to d_5	(-24, .24)	-4.72
d_5 to d_2	(-4, .42)	-1.38	d_7 to d_6	(-32, .36)	-7.75
d_5 to d_3	(-8, .67)	-3.54			

(iv) Sample Calculation for CPT Utility for OD Pair, 1-4

Let's consider a choice "segment d_6 to segment d_5".

Travel time loss at segment d_3 = -32 mins, and

Probability of the loss outcome = 0.78

Travel time loss at segment d_3 = -24 mins, and

Probability of the loss outcome = 0.55

Then prospect for the choice "segment d_6 to segment d_5" can be identified as (24, 0.55*0.78) or (-24, 0.43).

CPT Utility for Choice "Segment d_6 to Segment d_5" with Prospect (-24, 0.43) for OD Pair, 1-4

$$\pi_{-1} = w^{-}(P_{-1,d,i-j}) = \frac{P_{-1,d,i-j}^{\delta}}{[P_{-1,d,i-j}^{\delta} + (1 - P_{-1,d,i-j})^{\delta}]^{1/\delta}} = 0.410$$

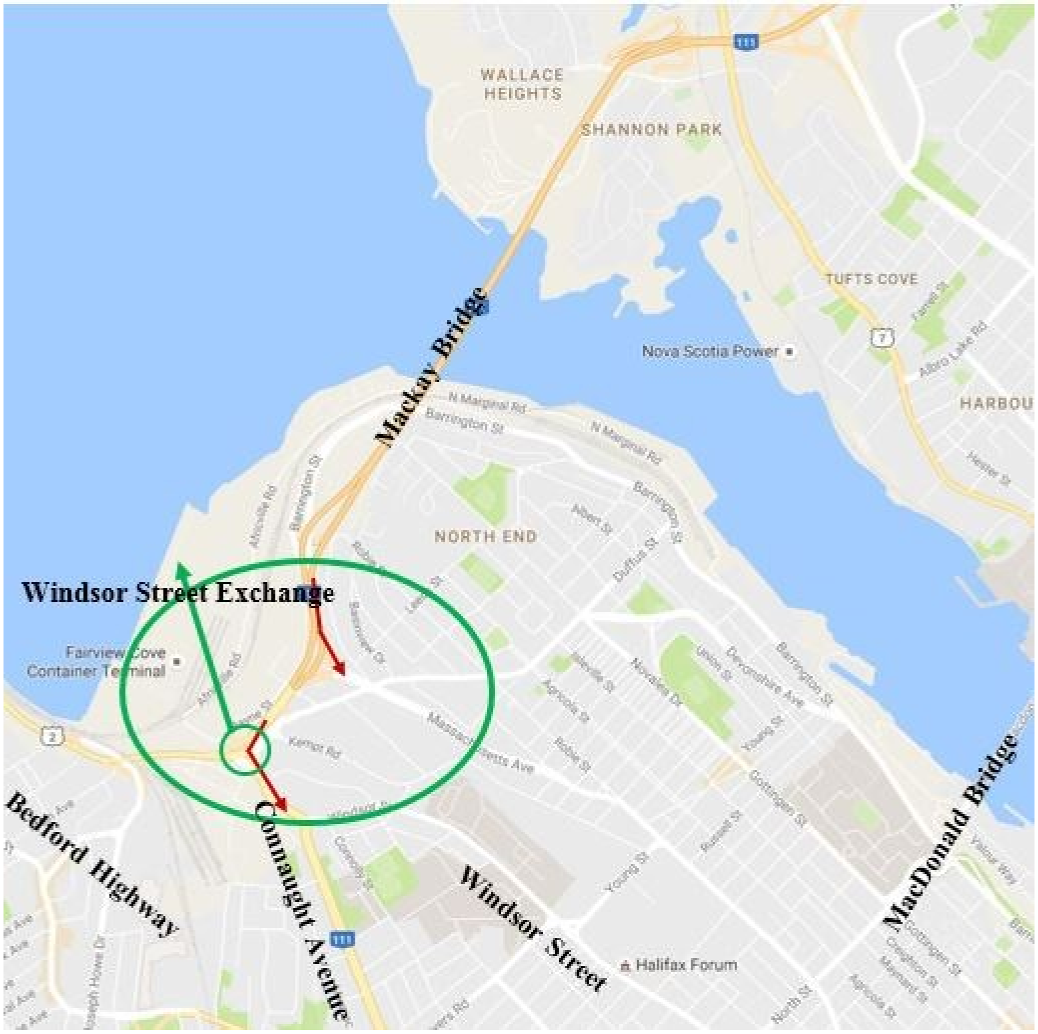
$$\pi_0 = w^{-}(P_{-1} + P_0) - w^{-}(P_{-1}) = w^{-}(1) - w^{-}(P_{-1}) = 0.590$$

$$v(x_{-1}) = -\lambda(x_{-1})^{\beta} = 16.39$$

$$v(x_0) = -\lambda(x_0)^{\beta} = 0$$

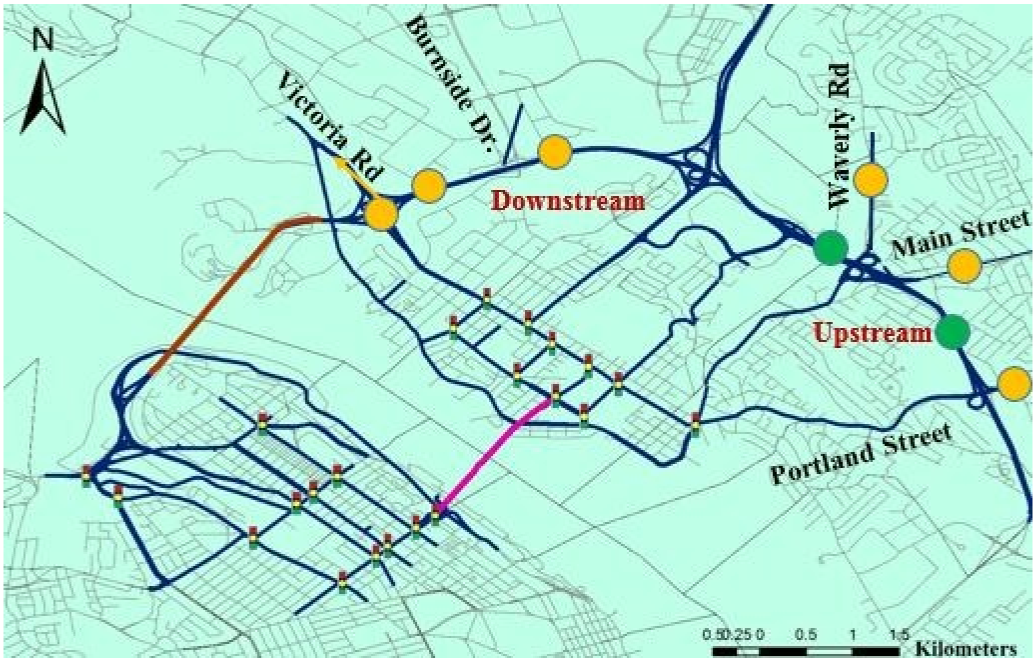
$$CWV_{1-4} = \sum_{q=-i}^{0} \pi_q^{-} v(x_q) = \pi_{-1} v(x_{-1}) + \pi_0 v(x_0) = 6.72$$

Appendix A12: Prioritizing Traffic Flow from the Mackay Bridge



Cycle length of Windsor Street Exchange can be revised

Appendix A13: Potential Locations for Variable Message Sign (VMS)



● Capacity exists

● Potential locations for VMS and traffic diversion

Traffic diversion at upstream locations could take place in the direction of locations where capacity exists with simultaneous traffic diversion planning at downstream locations. Traffic at downstream locations can be directed towards Burnside Drive and Victoria Rd to take the Highway 102.

Appendix A14: Access Management-Toll Section of the Mackay Bridge

Toll protocol of the Mackay Bridge could be removed during the closure of the Macdonald Bridge.