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Critical Infrastructure Renewal: A Framework for Fuzzy Logic Based Risk Assessment and Microscopic Traffic Simulation Modelling

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Abstract

This paper presents a comprehensive framework for risk assessment and micro simulation modelling to assess traffic impacts during re-decking of a major suspension bridge identified as Critical Infrastructure (CI) in Halifax, Canada. The bridge is being replaced while maintaining traffic during day time. As re-decking is relatively a rare and unknown construction event for a Cable Bridge, unexpected risk event and uncertainty would be associated with complex engineering manoeuvring during the re-decking of the bridge. Therefore, this study proposes a fuzzy logic approach to estimate the construction related bridge opening delay, and subsequently develops a micro simulation-based traffic network model to assess the traffic impacts on transport network. Weather data, traffic volume and signal data obtained from multiple data sources have been used during the risk assessment and micro simulation modelling. The results suggest that the likelihood of bridge opening delay could range from 18%-30% for an hour period to 40% for 3 hour period depending on the level of consequence on any day in December. The average potential delay is obtained as 22 minutes, 1.5 hours, and 2.6 hours for low consequence, medium consequence, and high consequence respectively. Based on the delay analysis, this study evaluates three alternative bridge opening delay scenarios. It is observed that the increment in number of operating vehicles becomes steady at 30% suggesting the network has reached its capacity. The results also reveals that any delay over 2 hours in bridge opening would add a slight change to the impacts on the network. This study will help policy-makers to develop risk mitigation plans and contingencies to ensure better management of traffic during 18 months long re-decking of this critical infrastructure.

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Keywords: re-decking; fuzzy logic; delay probability, micro simulation; traffic impacts.

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1. Introduction

Risk is inherent in large construction projects and refers to the potential complications in achieving the project goals. Risk has greatly plagued the construction industries which necessitates the risk assessment for the large scale construction projects. Especially, 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. Gradually increasing complexity in road construction and constant exposure to environmental conditions increase the vulnerability of large Critical Infrastructure construction projects to the unexpected hazardous events. Literature offers a plenty of evidence of the schedule slippage and thereby failures to attain the objectives of construction projects. Many factors such as weather, labor skill, and incidents are liable for construction delays and cost overruns of the 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. Although the delay of road construction projects cannot be avoided, 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 "Big Lift" (2015-2017) in order to replace the suspended spans of the Macdonald Bridge, a 1.3 km long Critical Infrastructure (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 and potential 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 paper presents a fuzzy logic approach to estimate the construction-related bridge opening delay, and develops a micro simulation model to assess the traffic impacts due to unexpected bridge opening delay during the "Big Lift" project. The re-decking has been started in October, 2015. Construction commences from 7:00 pm, with the bridge becoming operational again at 5:30 am the following morning. The main objectives of this study is (i) to develop a 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 micro simulation model. The delay risk analysis feeds the simulation process with the delay information required to test the possible case scenarios in AM peak period. The scenarios include (i) Base case scenario (no delayed opening) (ii) 1 hour delay (iii) 2 hour delay, and (iv) 3 hour delay in bridge opening to traffic in the morning. 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. 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 engineering. Many studies have investigated project risk, activity scheduling, and construction delays, risk factors and risk management methods. For example, a study identified a couple of factors such as heavy rain and delay in labor payment are the main causes responsible for the cost escalation and schedule delay in road construction (Kaliba et al., 2009). 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 critical infrastructure 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 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 can't be quantified for example, weather condition can be described as good or bad. There is no absolute numerical value that can be assigned to these subjective judgments rather these parameters can be best described in terms of linguistic terms. Literature suggests that the fuzzy set theory and fuzzy logic is an effective technique 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 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 sets for quantifying the imprecision in human reasoning and judgmental uncertainties of accident progression event trees. There are numerous application of fuzzy logic technique in bridge risk assessment and other construction projects (Wang and Taha, 2007; Carr and Tah, 2001; Cho et al., 2002; Kuchta, 2001). All 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 to estimate the bridge opening delay on a given day due to the interruption to its night re-decking.

The fuzzy-based approach appears to be advantageous for delay assessment of large construction projects that involve numerous uncertainties. Particularly, the method could be helpful to accommodate generality, imprecise data and rules, and most importantly expert's evaluation when risk predictive models are absent. The study evaluates the effects of key weather related parameters including wind, temperature, and precipitation within 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 micro-simulation 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 micro simulation techniques in construction projects. Holman (2012) examined different deck replacement methods, and found that the travel time increases from 94.26 sec at 500 veh/hr to 97.93 sec at 2200 veh/hr 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 phenomena in a work zone or an emergency period, which might exert severe impacts on traffic. Micro simulation techniques could better mimic the scenario 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 micro simulation models (Huang et al., 2009). Recently, a micro simulation 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 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 micro simulation methods are briefly discussed below.

3. Methodology

3.1. Fuzzy-based delay estimation

Imprecision in human decision and uncertainty creates mammoth challenges in completing construction projects on time. According to Ridwan (2004), conventional crisp choice models are not capable of handling this uncertainty and vagueness in decision making. Fuzzy logic method makes it possible to quantify the subjective judgment and incorporate the imprecision in human reasoning and thereby, improve the decision making. Cable Bridge re-decking is an occasional construction project. Simultaneous use of the bridge during the day makes the construction activities more sensitive to the 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 a risk assessment. The occurrence of the consequences for this kind of rare project refers to a degree of truth rather than referring directly to the either 'True' or 'False'. Fuzzy logic technique deals with this partial truth. 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 that pose risk based on the literature and engineering judgment. Then, it determines the frequency of occurrences of the identified factors. Weather data is obtained from the Environment Canada (Canadian Weather, 2015) for the month of December. This study selected December as volatile weather conditions and high traffic activity are evident in Halifax. Afterwards, the consequences of different factors on re-decking activity is categorized into three levels: Low, Medium, and High as identified in Table 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.

Table 1. Factors, frequency of occurrences, and adverse consequences (case 1, 2, and 3)

Factors		Frequency of Occurrence	Case 1	Case 2	Case 3
			Low consequence	Medium consequence	High consequence
Wind	Low	High	Low	Medium	High
	Medium	Medium	Low	Medium	High
	High	Low	Low	Medium	High
Temperature	Low	Low	Low	Medium	High
	Medium	Medium	Low	Medium	High
	High	Low	Low	Medium	High
Precipitation	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

The frequency of occurrence for each state of factors (alternatively referred as parameters) are determined based on the obtained 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 judgment. All cases considered in this study are presented in Table 1.

Next, each linguistic term of each attribute state of frequency of occurrence and adverse 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 judgment in assignment of the membership values. The membership values of frequency of occurrences and adverse consequences are shown in Table 2.

Table 2. Membership values of frequency of occurrence and adverse consequence

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	0.06	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 adverse 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 adverse consequences (C). The calculation refers to a Cartesian product (FxC) and the relation can be formulated according to the following equation 1.

$$\mu_M\ (x_m, y_n) = \min\,[\mu_F\ (x_m),\ \mu_C\,(y_n)] \tag{1}$$

Where,

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

$\mu_F\ (x_m)$= membership value of element x_m in fuzzy set F

$\mu_C\,(y_n)$= membership value of element y_n in fuzzy set C

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

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 3. Afterwards, 12 matrices are combined into a total matrix, T (see in Table 6a) based on the following equation 2.

$$T = [(F1\times C1)\ U\ \left(F2\times C2\right)\ldots\ldots\ldots\ldots.U(F12\times C12)] \tag{2}$$

Table 3. Fuzzy relation matrices of frequency of occurrence and adverse 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						
	0.1	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

Similarly, fuzzy relation matrix N(C, D) is developed by combining the fuzzy subsets of adverse 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 4 presents the membership functions representing the delay duration and Table 5 presents a sample of the N (C, D) matrices.

Next, all relation matrices N (C, D) are combined into a union S according to the following equation 3 and the union S is illustrated in Table 6 (b).

$$S = [(C1 \times D1)\ U\ \left(C2 \times D2\right)................] \tag{3}$$

Finally, a composition matrix (ToS) has been developed according to the following formulation:

$$\mu_{ToS}(x_m, z_o) = \max_{y_n}[\min[\mu_T(x_m, y_n),\ \mu_S(y_n, z_o)]] \tag{4}$$

Where,

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

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

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

Table 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 5. Fuzzy relation matrix of adverse consequences and delay elements

		Delay=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 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**
Adverse 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 hours							Row summation	Frequecy product
Frequency of occurrences	**0.0**	**0.5**	**1.0**	**1.5**	**2**	**2.5**	**3**		
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 6(c).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 6(c) satisfies the condition.

At the end, probability of delay duration, mean delay, and variance can be obtained by:

Probability, $$P(D=z_o)=\frac{\mu_V(z_o)}{\sum_{o=1}^{k}\mu_V(z_o)} \tag{5}$$

Mean delay, $$D_{avg}=\sum_{o=1}^{k}P\left(D=z_o\right)\times(z_o) \tag{6}$$

Variance, $$\sigma^2=\sum_{i=1}^{n}\mathrm{P}\left(D=z_o\right)\times\left(z_o\right)^2-D_{avg}{}^2 \tag{7}$$

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, and k = number of delay duration elements. Note that the element refers to ‘hours’ of delay in bridge opening. Table 7 shows the membership values of the desired subset for the corresponding delay hours.

Table 7. Fuzzy subset (V) from 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 7 and equations 5, 6, and 7, delay probabilities at half an hour interval, average delay, and variance can be estimated:
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%

This study reveals that the average delays could be 22 minutes, 1.5 hours, and 2.6 hours for low consequence, medium consequence, and high consequence respectively. Table 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. 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).

Table 8. Probabilities of delays in re-opening the bridge

Cases	0 hour delay	0.5 hour delay	1.0 hour delay	1.5 hour delay	2.0 hour delay	2.5 hour delay	3.0 hour delay
Low consequence	46%	36%	18%	_	_	_	_
Medium consequence	_	_	30%	45%	25%	_	_
High consequence	_	_	_	_	20%	40%	40%

3.2. Micro simulation model

3.2.1. Study network

The study area in Figure 1 is a mixed urban road network including Halifax and Dartmouth linked by two bridges, the Macdonald and the Mackay. The developed network model includes an area 4 km in width and 6 km in length. A Google Earth image of the study area is used to confirm the true geometry and location of the network elements. Direction and turning restrictions have been derived from the Google Map Street View and field visits. The final network model consists of 250 links, 570 connectors, and 28 major intersections within the VSSIM 6.0 platform.

3.2.2. Data

The network is also equipped with 28 signal controllers, stop signs, roadway restrictions, 91 bus stops, about 1203 resolved turning conflicts, and other important road network features. Signal controllers are coded in VISSIM with signal time obtained from the Public Work Traffic Study of Halifax Regional Municipality (HRM), October 2014.

Moreover, the origin-destination traffic flow is obtained from the Halifax Network Model (Mahbubur and Habib, 2015) that uses 2006 as the base year. Therefore, a population growth factor is applied to forecast the traffic flow at

2014. Traffic composition consists of auto, transit and truck. In addition, traffic count obtained from HRM is used for validation of the model.

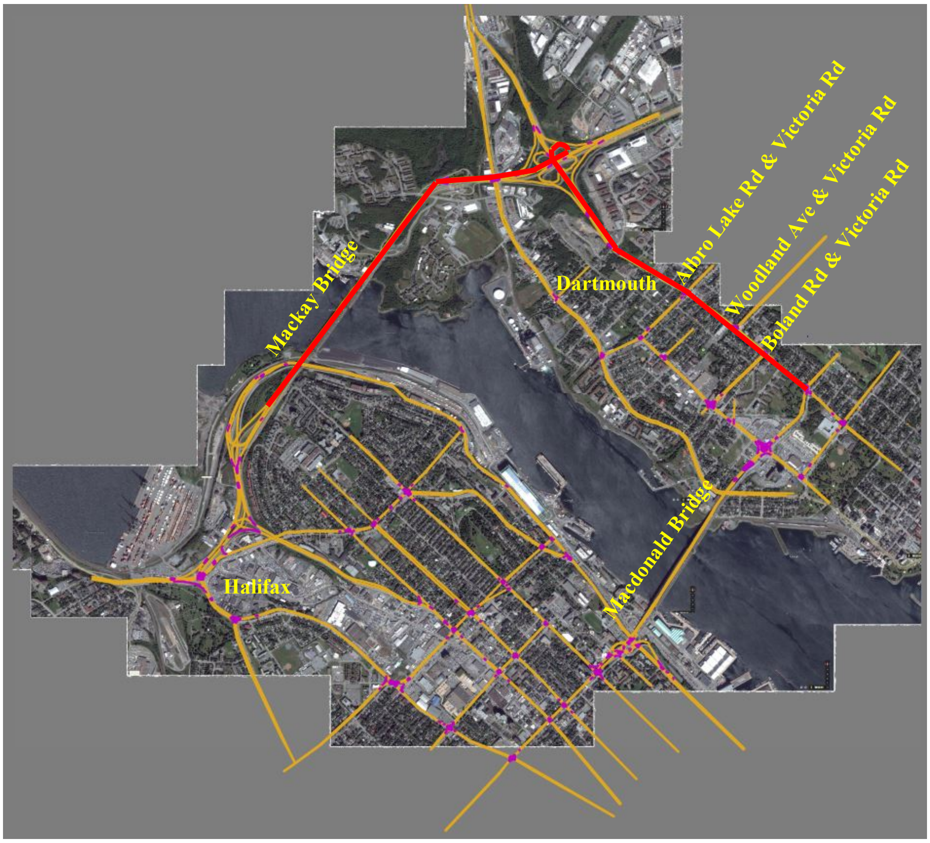

Figure 1. Study area and road network

3.2.3. *Traffic assignment*

Traffic flow is assigned in the network on the basis of traffic demand obtained from the Halifax Network Model and 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). Initial simulation run resulted in lower traffic flow in the network. Necessary adjustment to traffic flow input is performed based on the comparison of simulated and observed traffic through an iterative process. Further improvement of the model is done by calibration of the driving behavior parameters.

3.2.4. *Calibration of driving behavior parameters and validation of the model*

Calibration is the most critical and time consuming stage of micro simulation modelling. In general, model calibration includes the individual model calibration with disaggregate data (i.e. vehicle trajectory) followed by the general parameter calibration with aggregate data (i.e. time headway, speed, etc.) in the simulator.

As the detailed disaggregate data is unavailable, general driving behavior is calibrated in this study. Driving behavior is usually affected by the car following and lane change maneuvering in the simulator. 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.

However, simulation has 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 locations and a few other intersections and compared to the field traffic count. The combination of the parameters used for different trials of simulation are as below in Table 9.

Table 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

The observed and simulated traffic flow is compared in terms of GEH value, a modified chi-square statistics used by British engineers (UK Highway Agency, 1996) and R^2 value for the different combinations of driving behavior parameters in Table 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 8:

$$GEH = \sqrt{\frac{2 \times (S-O)^2}{(S+O)}} \tag{8}$$

Where,

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

Goodness of fit can be evaluated according to GEH values with the following criteria (Oketch and Carrick, 2005).

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

Screen line and a few strategic locations have been selected for validation purpose and a set of targets were established to be achieved for selecting the successful combination of the parameters. The targets are mentioned as below:

(i) At least 80% of all considered screen line and a few strategic locations would have GEH value 5 or less
(ii) R^2 would be greater than 80%

(iii) An attempt will be made to keep the number of locations minimum having GEH value greater than 10

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 GEH and R^2. Moreover, further calibration didn't make any significant contribution to the resemblance of the model and actual network. The final selected combination that gives the good fit of the model is combination# 9 in Table 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 and the results of GEH and R^2 values are as shown in Table 10. 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. This 25% traffic flow may need further investigation. In addition, R^2 has been found to be 87 % which is greater than the target value (80%).

Table 10. Values of GEH and R^2

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

4. Microsimulation results and discussions

Three alternative scenarios i.e., 1 hour delay, 2 hour delay, and 3 hour delay in re-opening the bridge in the morning are simulated for morning rush hour, 5:30 am -9:30 am within the microscopic traffic simulation model. In the case of Macdonald Bridge closure, Victoria Rd followed by the Mackay Bridge (red marked as shown Figure 1) is a major alternative link for the traffic from bridge surrounding area to reach at Halifax Downtown Core. This study conducted a comprehensive traffic congestion analysis on network as well as on link level. Mackay Bridge and Victoria Rd are considered for link level traffic impact analysis. Traffic impacts are evaluated in terms of changes in Measures of Effectiveness (MOEs). The link level MOEs include average queue length, traffic flow. On the other hand, network level MOEs include average delay, average speed, vehicle kilometres travelled (VKT) and traffic flow indicators.

4.1. Network level impacts

Table 11 reveals traffic impacts on overall network resulting from delays in re-opening the Macdonald Bridge. During the bridge closure, percent increment in average delay and percent reduction in average speed indicate a growing congestion in the network and delay increment in re-opening the bridge exacerbates the congestion. Spillover appears in the network in terms of increment in the number of operating vehicles. 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 at 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. This is resulted from travel time increment in relation to the increase in bridge closing hours. A longer travel time increases not only the driving time but also the distance travelled. Consequently, longer travel distance would contribute to more carbon emission.

Table 11. Network performance

Criteria	Base case scenario (no delay)	Scenario 1 (1 hour delay)	Scenario 2 (2 hour delay)	Scenario 3 (3 hour delay)
Increment in number of operating vehicles in the network (%) with respect to base case	-	12	30	30
Reduction in number of vehicles arrived at destinations (%) with respect to base case	-	8	9	17
Reduction in average speed (%) with respect to base case	-	5.2	11	17
VKT (km)	58225	59662	64648	60330

4.1.1. Average travel time and average delay

Average travel time and average delay are illustrated in Table 12. The results suggest that 1 hour delay in re-opening the bridge causes insignificant traffic impacts in the network. 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 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 hour is relatively higher compared to that of from 2 to 3 hour which is 49.17 min to 53.67 min. This is because major part of the traffic impacts occurs after 2 hour delay in re-opening the bridge. Average delay also increases following the same pattern and it is around 47 minutes at critical condition.

Table 12. Average travel time and average delay

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%

4.2. Link level impacts

4.2.1. Impacts on Mackay Bridge

The Mackay Bridge is one of the two major roadway links between Downtown Halifax and Dartmouth. Table 13 summarizes the hourly traffic volume across the Mackay Bridge for both the base case (no delayed opening) and the 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 & 3 shows almost same traffic volume shifted to the Mackay Bridge which indicates that congestion in the network reaches at 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. Though the Macdonald Bridge is open for the next hours (6:30 am-9:30 am), there are still few shifted vehicles on the Mackay Bridge within these three hours.

Table 13. Traffic volume (vehicles / hour) on Mackay Bridge

Time Interval	Base case scenario (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
5:30-6:30	1027	2013	2244	2224	+986	+1217	+1197
6:30-7:30	2425	2445	3120	3101	+20	+695	+676
7:30-8:30	1055	1430	2247	2149	+375	+1192	+1094
8:30-9:30	1197	1571	1257	1257	+374	+60	+60

4.2.2. 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 1) 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. Among different methods, 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 14.

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 & 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 14. Queue length at three intersections on Victoria Rd

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

4.3. Delay cost

The MacDonald Bridge, as a critical infrastructure and a vital link of the Halifax transport network, renders a significant service in daily traffic operation as well as contributes to enhance economic security of the community. Therefore, any delayed access to the bridge would incur an economic loss on road users and disrupt the regular traffic movement. In this study, the traffic impact assessment found a saturated traffic congestion in the network due to closure of the bridge. A delay cost is estimated for the 1 hour delay in re-opening the bridge. A study (Habib and Richardson, 2012) calculated Value of Travel Time (VOT) for the Halifax residents' as \$8.46. Based on that the total economic loss in regards to 1 hour delay in bridge opening is estimated as \$22,000 for the AM peak period. Therefore, appropriate mitigation strategies are of paramount importance to minimize the delay risk and congestion cost.

5. Conclusion and future development

This study presented a framework for fuzzy logic-based risk assessment and micro simulation-based traffic modelling for assessing the traffic impacts due to construction related bridge opening delay in the morning peak period. This study contributes to the gap existing in literature by assessing the traffic impacts of sudden delay in re-decking of a critical infrastructure. Initially, the risk assessment estimated the probabilities of bridge opening delays depending on the level of consequences (i.e. low, medium, and high). For example, 1 hour delay probability in bridge opening is 18% and 30% with respect to cases- low consequence, and medium consequence respectively. On the other hand, 2 and 2.5 hour delay in re-opening the bridge is equally probable (40%) in the case of high consequence. The delay risk results then inform the scenario building process for traffic impact assessment within a microsimulation platform. The scenarios include (i) 1 hour delay (ii) 2 hour delay, and (iii) 3 hour delay in re-opening the bridge.

Next, each delay scenario is simulated for traffic impact assessment and compared to base case scenario (no delayed opening). The simulation results yield considerable traffic impacts 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. Results in Table 13 reveal that only 31% re-routed vehicle could cross the Mackay Bridge in the hour, 6:30 am -7:30 am due to a high base peak hour traffic volume on the bridge. As a result, queue grows rapidly and network gets saturated. This study found all the intersections saturated in terms of queue length for the whole evaluation period in the case of a 3 hour closure of the Macdonald Bridge. Moreover, average travel time increases by 33% and 45% in the case of scenario 2 (2 hour delay) and scenario 3 (3 hour delay) respectively with respect to the base case scenario (no delayed opening). From the operational point of view, 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 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 study has also estimated a delay cost for 1 hour closure of the Macdonald Bridge as the amount of $22,000 for AM peak period which would be higher for a longer delayed opening of the bridge. Therefore, a comprehensive warning and mitigation strategy should be in place to reduce the delay and delay cost and ensure a safe and smooth traffic flow in the network. In this regard, emerging technologies, for example Information and Communication Technology (ICT), Twitter can be used to inform the driver upfront about the incident to reduce the demand in the network. Further studies would help the policy making and risk management towards the mitigation of the traffic impact level during the emergency.

This study has certain limitations. For example, this model considers the drivers having no prior information of the bridge closure. It will be interesting if the modelling system could be developed for alternative scenarios based on the level of awareness. That model could further account uncertainties during the critical condition.

This study concludes that the bridge opening delay is likely to occur and have subsequent significant impact on surrounding transport network. A delayed opening of the bridge during the first week of the deck replacement justifies the findings of this study. We can draw lessons from it and prepared ourselves for this nature of unforeseen risk events. This modelling approach and framework is generic and could be adopted in other large scale construction projects including bridge projects in other areas.

Nevertheless, this research contributes significantly by offering a comprehensive framework for risk assessment and traffic simulation. Since the re-decking will continue for the next 18 months, the study could be a useful guide for discussions on risk management, traffic management and warning procedure to minimize the potential impacts on daily lives and the economy.

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