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Microsimulating Cross-Border Truck Movements between Ontario and the United States: An Application using Connected Vehicle Technology

By

Sidra Anis

A Thesis

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Microsimulating Cross-Border Truck Movements between Ontario and the United States: An Application using Connected Vehicle Technology

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ABSTRACT

The land-border crossings between Canada and the United States facilitate over half of the goods transported between the two countries. Since trucks are the primary mode of transportation for the movement of these goods, studying the traffic flows and the characteristics of border crossings is of paramount importance for decision makers, planners and researchers. The province of Ontario is home to the busiest border crossings in Canada including the Ambassador Bridge in Windsor, Ontario and the Blue Water Bridge in Sarnia, Ontario. GPS data collected from a large sample of trucks shows the route choice characteristics for these border crossings. The same dataset also shows the destination locations for these trucks. This thesis utilizes VISSIM, a microscopic traffic simulator, and its dynamic traffic assignment, an imbedded route choice model, to replicate these route choice conditions. Once the model is validated with the shares of flows from the observed (i.e., reference) datasets, the route choice behavior is analyzed under different delay conditions. The research also analyzed the effects of connected vehicle technology, at different penetration rates, on the efficiency of border crossing operations. As the connected vehicles increased in the traffic stream, it was observed that traffic was more streamlined and would switch to use the Blue Water Bridge during the simulation of an incident on Highway 401. The penetration rate was increased in 20% increments and with 100% penetration, 7% of total truck traffic had switched to Blue Water Bridge to travel to their U.S. destination.

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LIST OF ABBREVIATIONS

O-D	Origin-Destination
BTOA	Bridge and tunnel Operators Association
CVS	Commercial Vehicle Survey
RTMS	Remote Traffic Microwave Sensor
GPS	Global Positioning System
FAST	Free and Secure Trade Program
AADT	Annual Average Daily Traffic
HGV	High-Gravity Vehicle
PCU	Passenger Car Unit
MSA	Methods of Successive Averages
DTA	Dynamic Traffic Assignment
DCD	Double Crossover Diamond
ITS	Intelligent Transportation System
GHIB	Gordie Howe International Bridge
V2V	Vehicle-to-Vehicle
V2I	Vehicle-to-Infrastructure

1. INTRODUCTION

Overview

The study of land-border crossings and the transportation activities associated with them is important for long-term economic planning. Transportation plays a significant role in the trade between Canada and its international partners, especially the United States. It is reported that approximately 57% of the trade between Canada and the United Sates is handled by heavy commercial trucks (Transport Canada, 2012). In 2017, approximately 11 million two-way truck movements were recorded at the land-border crossings between Canada and U.S., representing $387 billion in imports and exports (Transport Canada, 2018). By Canadian province, Ontario has the highest level of trade interaction with the United States through land border crossings.

Freight trucking companies in Ontario make up approximately 42% of the share of all companies in Canada. The province of Ontario is known to have the busiest road network with Highway 401 being one of the busiest corridors in all of North America. The corridor not only services Toronto, the largest metropolitan area in Canada, but also facilitates the movement of goods between Canada and the United States (Transport Canada, 2018). A large percentage of the goods from the Toronto region and beyond are transported to a number of key U.S. markets including Chicago, Columbus, Nashville to name a few (Gingerich, et al., 2016; Transport Canada, 2016).

The province of Ontario provides critical links to major U.S. destinations through the Ambassador Bridge in Windsor, Ontario and the Blue Water Bridge in Sarnia, Ontario, processing 28% and 13% of the freight traffic, respectively (Maoh, et al., 2016). The

Ambassador Bridge has been operating since November 1929 and is the only option for trucks crossing the border via Windsor. The importance of the Windsor corridor for the trade between Canada and U.S. has prompted the Ontario government to invest a $1.4 billion parkway that extends Highway 401 to form an “end-to-end border transportation system at Canada’s busiest land border crossing and premier trade corridor.” (Rt. Hon. Herb Gray Parkway, 2018). The Parkway will be connected to the future Gordie Howe International Bridge, a new border crossing currently under construction in Windsor, Ontario. The cost of this border crossing is expected to be $5.4 billion and will provide a direct route from Highway 401 to Detroit (Windsor-Detroit Brdige Authority, 2018). The addition of this crossing to Ontario’s transportation network is expected to improve the flow of freight traffic and relieve congestion from Windsor’s local traffic network currently handling border traffic going through the Ambassador bridge.

In the last decade, a handful of studies have been done on various aspects of border crossings. Researchers have studied the flow of goods to and from freight hubs, travel time and delays at border crossings (Gingerich, et al., 2016), route choice behavior between alternative border crossing locations (Gingerich, et al., 2015), effectiveness of priority crossing lanes at borders (Brijmohan & Khan, 2011), and implementation of intelligent transportation systems (ITS) at border crossings for prediction of delays (Khan, 2010). Advanced discrete choice models have been implemented to study different aspects of border crossings to understand processes better and determine ways of improving delays and crossing times. Microscopic traffic simulation models have been used in urban settings to optimize the flow of traffic but have rarely, if at all, been used for to study regional truck movements across the Ontario-U.S. border.

There are constant improvements being made to the safety and efficiency of road transportation. Vehicles are being equipped with cutting edge technology to improve the drivers' experience. In recent years, the automotive industry has introduced technology to connect vehicles by enabling them to communicate with other vehicles with the help of on-board sensors and roadside infrastructure. These connected vehicles convey messages to drivers about downstream conditions that may add interruptions to their trips. It is expected that the integration of such technology will improve the efficiency of vehicle movement on road facilities. To date, the focus of existing studies in the literature has been on analyzing the effects of connected and autonomous vehicles in urban environments. For instance, Guler et al. (2014) used connected vehicle technology in a microscopic simulation environment to study the efficiency of traffic at urban intersections. By comparison, there is little information available on the effects of such technology in the context of cross-border vehicle movement.

Research Objective

The primary objectives of this thesis are:

1. Advance the current knowledge on the movement of connected heavy commercial trucks moving between Ontario and the United States.
2. Develop a regional model which can be used to simulate the flow of individual heavy commercial trucks between Ontario, Canada and major U.S. markets via the Windsor and Sarnia border crossings.
3. Incorporate connected vehicle routines in the developed regional model to examine the extent of improvements in border crossing traffic flow in the presence of such emerging automotive technology.

Thesis Outline

The remainder of this thesis is organized into the following chapters: Chapter 2 provides a review of the existing literature that have been conducted to study border crossings and their importance to the economy; cross-border traffic patterns and recent trends; microsimulation modeling; and connected vehicles. Chapter 3 presents the methods of analysis used to model the dynamics of cross-border traffic movement under different delay conditions and scenarios. The chapter also presents the developed transportation network needed for the microscopic traffic simulation model as well as the data collected, organized and used as input to the microscopic simulations. The results extracted from the analysis, namely from simulating a variety of cross-border dynamic traffic assignment scenarios including connected vehicle scenarios, are presented and discussed in Chapter 4. The conclusions, contributions, and the recommendations for future work are presented in Chapter 5.

2. LITERATURE REVIEW

The Canadian Economy and the Canada – U.S. Border

The trade between Canada and its international partners in 2017 was worth $1,107 billion dollar where $703 billion was just between Canada and the United States, the highest value traded in the history of the two countries (Transport Canada, 2018). The two countries heavily rely on each other for sustaining their economic growth and success. The uninterrupted flow of goods between the two countries is crucial for this trade to continue and grow. There are many modes through which trade is facilitated but the majority of which is handled through road transportation.

Ontario is the most trade-intensive province in Canada. The provincial GDP proportions of exports and imports can be compared to countries such as Germany, China and Italy and represent 50% of Ontario's GDP (Anderson, 2014). One of the biggest markets for Ontario's exports is the U.S. In 2016, 80% of goods were exported through Ontario and Québec, Canada's Continental Trade and Gateway Corridor, to the U.S. (Transport Canada, 2017). The border crossings in Ontario facilitate approximately 58% of Canada's total trade with the U.S. including Ambassador Bridge with 28% of movement, the Peace Bridge with 17% and the Blue Water Bridge with 13% (Maoh et al., 2016). The movement of these goods is heavily dependent on efficient border crossing facilities, especially for goods required for just-in-time deliveries and supply-chain logistics. Therefore, it is important that the flow of these goods remains uninterrupted for sustainable economic growth.

Research Efforts on Border Crossings and Freight Movement

The growth in freight transportation has led to an increased interest in studying truck movements between Canada and the United States in recent years. Since freight trucks are mainly owned and operated by private firms, confidentiality issues usually curtail the ability of researchers and practitioners to acquire fleet movement data. Historically, efforts have been made to collect data on cross-border shipments through vehicle surveys, traffic counts, and through statistical agency programs (Maoh, et al., 2016; Goodchild, et al., 2009). However, records from these data sources are expensive and not easy to collect. In recent years, passive GPS data have been used to validate other data sources and also to expand existing databases on cross-border movements. However, such data is referred to as opportunistic as it is not normally produced for research purposes. Also, the basic raw and masked nature of this data (due to privacy concerns) necessitates geo-spatial analysis such as the one conducted by Gingerich et al. (2016). Once truck GPS data is analyzed and mined, the extracted information can be versatile and effective to study freight movement, stops and delays in details. Gingerich et al. (2016) used passive GPS data to determine primary and secondary stops along truck routes to identify origin and destination locations. The same data have also been used to validate route choice models between Toronto, Ontario and Chicago, Illinois (Gingerich, et al., 2015). Travel time and traffic proportion on each route have also been examined to study route choices made by decision makers and the factors that affect these choices.

As the movement of goods increases, the need for improved border processes become essential. Increased border inspections and delays cause queues that result in major losses to industries on both sides of the border. Researchers in the field have studied various aspects of the border to determine ways of improving processes at the border crossings. The governments of both countries have implemented a Customs Trade Partnership Against Terrorism (C-TPAT) program that companies can register with voluntarily and must comply with certain security measures to build trust between companies and governments (Goodchild, et al., 2009). The trucks that belong to these companies can use FAST (Free and Secure Trade program) lanes at the border crossings with minimal delays. The objective of this program is to aid in reducing the overall delay at the borders.

The research in the field studies different aspects of border crossings in varying contexts. It can be said that a great need exists in expanding the research and analyzing the borders and their effects on the economy, environment and infrastructure. The current studies provide a foundation to carry the research forward and continue to add to the existing transportation literature.

Traffic Simulations

Traffic simulation models are becoming increasingly prevalent in the transportation industry. As defined by May (1990): "*Simulations are numerical techniques for conducting experiments on a digital computer, which may include stochastic characteristics, be microscopic or macroscopic in nature, and involve mathematical models that describe the behavior of a system over extended periods of time.*" Planners, researchers, and policy makers are easily able to model real-world scenarios and collect data without having to physically observe conditions in the field. These models provide researchers with the capability to model large-scale region-wide networks and observe any changes that may result due to infrastructure or policy changes. Traffic simulation models are also able to duplicate specific field conditions such as traffic volumes, capacity, delays, queues and so forth. These models can be validated with existing conditions to establish a base case benchmark and then can be used to simulate changes such as expansions, lane closures and accidents. Traffic simulation models are of three types: macroscopic, microscopic, and mesoscopic. As outlined by Barceló, (2010), macroscopic models analyze traffic flow in aggregated forms based on hydrodynamic analogy such as speed, density, and flow. Microscopic simulations are disaggregate in nature and are able to analyze movements of each individual vehicle in the network. However, these microscopic models require detailed data to be implemented. Mesoscopic models are less data demanding and are able to simplify and combine the two previous approaches as it can analyze traffic flow dynamics as well as packets of vehicles. Among the three classes of models, the microscopic approach is more adequate for testing the performance at cross-border facilities and therefore is the focus of the research work in this thesis.

Microscopic Traffic Simulations

Microscopic traffic models, more commonly known as microsimulation models, simulate the actions of individual vehicles such as acceleration, deceleration and lane changes in response to its surrounding traffic environment (Barceló, 2010). These models are primarily based on car-following models that describe various motions of a vehicle. The pioneering work on car-following models was done by Pipes (1953) by describing the "following distance" for a trailing vehicle. The theory relates minimum safe distance linearly to speed (Barceló, 2010). The concept is an intuitive one because as the the distance between two vehicles increases, the speed of the following vehicle also increases. The model was further expanded by Chandler et al. (1958) at the General Motors research lab where the field data was used to develop mathematical models to describe acceleration as a function of difference in velocity of two vehicles. These models laid the foundation for a stimulus-response equation developed by Gerlough & Huber (1975) where the response of the driver is the reaction to a motion of the leading vehicle. Gazis et al. (1961) of General Motors developed a non-linear model and emphasized steady-state equations. A number of advances were made in the development of realistic car-following models throughout the next few years. The main focus was to establish algorithms that were realistic in their representation of vehicle motions and field conditions. The psycho-physical model implemented by VISSIM was developed by Weidemann in 1974 and further explored by Fellendorf in 1994 (Barceló, 2010). This model aims to define driver perception of the leading vehicle motion. The driver is able to decelerate once it perceives the leader vehicle slowing down. It is worth noting that VISSIM is a mainstream microscopic traffic simulation software that is used by researchers and practitioners to study transportation systems at the micro-level. The software is "*the world's leading technology to plan and optimise the movement of people and goods*" (PTV Group, 2019)

Microsimulation models have been used in various traffic management and transportation engineering scenarios worldwide. These models can be used to analyze any traffic scenario whether it be testing the impacts of signalized intersections on vehicle safety performance (Cunto & Saccomanno, 2008), or modeling lane change and merging behavior in congested traffic conditions (Hidas, 2002), or traffic emission modelling with speed management in an urban area (Panis, et al., 2006). Microsimulation can also be combined with other techniques to find optimized solutions. Zhizhou et al. (2005) calibrated VISSIM for the Shanghai expressway using genetic algorithm techniques to determine which parameters affect simulation accuracy.

Traffic conditions in developing countries vary significantly from developed countries. Heterogeneous traffic composition, lack of traffic management, non-compliance of traffic laws, and densely populated urban areas, make it challenging for researchers to study traffic flows and identify effective methods of improvements. In such circumstances, microsimulation models can provide the necessary tools to evaluate complex traffic scenarios and allow users to perform extensive analysis for research, and planning, and management. Hossain (1999) estimated the capacity of roundabouts for mixed-traffic conditions using microsimulation techniques. Arasan & Arkatkar (2010) presented the impacts of road width and volume on PCU under heterogeneous traffic conditions. The heterogeneous traffic conditions also result in irregular pedestrian crossing behavior in such environments. Yang et al. (2006) used microsimulations to model pedestrian crossing behavior in China. The successful modeling of such conditions can allow researchers to determine the factors that can help improve the traffic environment and allow for safer traffic conditions, for both pedestrians and vehicles.

Traffic Operation

Traffic operation and management is a broad field with varied microsimulation applications such as calibrating and validating a VISSIM model for four operational Double Crossover Diamond (DCD) interchanges in the United States by using field collected data (Schroeder, et al., 2014). This validated model can be used as a benchmark for potential DCD locations. The deployment of alternative traffic control systems such as DCD interchanges can cause issues if not planned out in advance. It also serves as a useful tool to understand the traffic patterns that might emerge due to construction and rerouting activities for urban and freeway work zones such as the microsimulation validation model presented by (Park & Qi, 2006). The modelling of complex freeway sections with merging and High Occupancy Vehicle (HOV) lanes can also be done with microsimulation tools such as the procedure presented by Gomes et al. (2004). The authors developed a procedure for developing and calibrating a model of a freeway section in VISSIM for a 15 mile stretch of I-210 West in Pasadena, California.

The effects of improved intersection technology can also be evaluated using microsimulations as modeled by Li et al. (2013). The external driver model in VISSIM was used to test the safety and performance of the autonomous control of urban traffic (ACUTA). The intersection was modeled to communicate with the vehicle and to inform if it was able to traverse the intersection safely. The signal timing plans and any improvements affect all transportation modes in the model. Ishaque & Noland (2005) studied the effects of signal timing plans on both vehicles and pedestrians in a multimodal microsimulation study that included cabs, trucks, and buses. The vehicle flow and cycle times were varied with other constant parameters to determine the optimal cycle time that would benefit all users. Park et al. (2001) used a microsimulation software, CORSIM, to interface with a genetic algorithm-based signal optimization method (GA-SOM). The objective was to test the performance of the GA-SOM to determine how well it predicts the functionality of a fixed signal plan. To test the model, a Chicago network of nine signalized intersections was used in the model.

Cortes et al. (2010) modeled pedestrians and public transit in urban microsimulation models to accurately represent the interactions of the different actors that are normally present in real-world situations. Typically, microsimulation software packages focused on modeling vehicle interaction with other vehicles and the infrastructure. By comparison, the modeling of pedestrians and other non-vehicle users was not as common in these models given the complexities of the behavior pertaining to these users. Ishaque & Noland (2009) present an approach to modify pedestrian behavior for a realistic replication of pedestrian speed-flow models. The study defined pedestrians as vehicles and modified the parameters to model pedestrian behavior to study the interaction at an intersection with high levels of pedestrian-vehicle interaction.

Traffic Safety

The impacts of road safety measures on road facilities have been extensively studied in the literature with the help of microsimulation models. The purpose of these studies is to examine various safety measures to improve road facilities and reduce collisions. Microsimulation tools allow researchers and planners to evaluate the effects of road safety measures without having to implement it in the field. There are cost and time benefits associated with such practices as the effects of the measure or modification can be evaluated without any changes in the field. García et al. (2011) presented the effects of traffic calming measures of traffic flow and capacity using a VISSIM microsimulation model. The capacity of the network and the spacing of the measure were varied to analyze various combinations and study the effects. Astarita et al. (2011) presented a microsimulation model that was calibrated to study traffic safety levels for overtaking maneuvers in rural areas. The model was calibrated using video image processing technology and was validated with real traffic scenarios.

The safety performance of intersections can also be evaluated with microsimulation models as presented by Young & Archer (2009). The authors modeled a vehicle actuated traffic signal that was equipped with an incident reduction function to determine if safety performance of the intersection would improve. A sample of Toronto intersections were examined by Shahdah et al. (2015) to study the effect of counter-measures using conflicts obtained from VISSIM and observed crashes from the field. A safety surrogate assessment model was integrated with VISSIM and a genetic algorithm was utilized to optimize signal timings for reduction in risk of crashes (Stevanovic et al., 2013).

Cross-Border Traffic Analysis

As noted earlier, the majority of the work in literature focuses on microsimulation models of intersections, freeway sections, multimodal scenarios and so on to study issues related to traffic safety, traffic operation, and autonomous vehicle movements. Khan (2010) is an exception as the study was to first to calibrate a microsimulation model in VISSIM to generate detailed traffic flow data at the Ambassador Bridge crossing. The generated data from the microsimulations were then employed to develop machine learning models to determine the effectiveness of intelligent transportation systems (ITS) strategies in predicting delay and queues in real time. The model was found to be effective at the simulation level.

A summary of the microsimulation literature is also presented in Table 2-1

Table 2-1 Literature Summary for Traffic Microsimulation

Author(s)	**Year**	**Objective**	**Area**	**Methodology Overview**
Peter Hidas	2002	To present a lane change and merginig model under congested conditions developed for Simulation of Intelligent Transport Systems (SITRAS).	Traffic Operation	A forced lane-change model was developed for SITRAS, a microscopic simulator, to replicate congested conditions. A 500 meter section of a three-lane urban street was simulated with no incidents in the first run. The second run saw a lane closed because of an incident and the third run had two lanes blocked in the same place. The simulation results from each simulation run were analyzed to determine the efficiency of the model.
Luc Int Panis Steven Broekx Ronghui Liu	2006	To examine the effect of speed-management on traffic-induced emissions.	Emissions	An instantaneous emission model was developed and integrated with a microscopic traffic simulation. The model captures speed and acceleration data for each individual vehicle in the simulation with other traffic and traffic control in the network. The effect of speed and acceleration on emissions is examined.
Usama Shahdah Frank Saccomanno Bahgwat Persaud	2015	To develop a statistical relationship between observed crashes and microsimulation traffic conflicts to evaluate safety performance, i.e. the effect of countermeasures, of intersections.	Safety	53 untreated intersections in Toronto were used to examine the relationship between simulated and observed conflicts, and between observed crashes and approach volumes. The crash data used was for the period 2001-2004. Left-turn opposing crash data was simulated in the course of this research. For each intersection, the AM peak hour was simulated, and 30 and 50 simulation runs with 30 and 50 random seeds, respectively, were simulated to capture the stochasticity of traffic with a 5min warming period. To estimate countermeasure effects, 47 treated sites were simulated pre and post treatment. The results were compared to a previous study's Empirical Bayes before-and-after crash analysis results for the same site sample.
Guohua Song Lei Yu Yanhong Zhang	2012	To determine if traditional microsimulation models can be reliable in estimating emissions using vehicle-specific power (VSP) distributions, a widely accepted explanatory variable of fuel consumption.	Emissions	The data used for the analysis was collected from real-world traffic observations and VISSIM's traffic simulation model. VSP distributions are comparable at the same speed once the road and vehicle types considered are identical in the dataset. A light duty vehicle, as described by Motor Vehicle Emission Simulator (MOVES) 2010, and freeways and expressways were used for the analysis. VSP was calculated using MOVES2010 and speed information from GPS data. VISSIM was used to collect speed data for the simulated section and VSP was calculated. The error between the two datasets was then calculated for each speed bin.

Table 2-1 Continued

Bastian J. Schroeder Katayoun Salamati Joseph Hummer	2014	To present a calibration approach for the operation of double-crossover diamond interchanges and validate data collected from 4 interchanges in the United States in a microsimulation environment.	Traffic Operation	The simulation was calibrated with O-D volumes, lane change distance, speeds at the interchanges and the arterials and field implemented signal timing plans. The validation parameters included intercahnge travel time (including left turning routes), route travel times and 95th percentile queue lengths.
Siddharth S M P Gitakrishnan Ramadurai	2013	To perform sensitivity analysis to find significant parameters and automate the calibration process in VISSIM.	Traffic Operation	A two-hour dataset for heterogeneous traffic for the IT corridor in Chennai, India was collected for the analysis. The first hour data was used for calibration and the second hour data was used for validation. ANOVA (Analysis of Variance) and EE (Elementary Effects) were used to perform sensitivity analysis to determine significant parameters. VISSIM’s COM interface and a Genetic Algorithm was then used to calibrate the model with the significant parameters. The model was then validated with the second-hour dataset for the same corridor.
Wu Zhizhou Sun Jian Yang Xiaoguang	2005	To calibrat VISSIM parameters for traffic operations on an expressway in Shanghai, China using Genetic Algorithm as an optimization technique.	Traffic Operation	A N-S section of a freeway in Shanghai was selected and coded in VISSIM 3.7. A set of parameters such as lane change distance, headway time and safety distance were chosen. A set of values were chosen as default and the genetic algorithm was used to optimize the VISSIM output and generate new values for the simulation until the best solutions were reached.
Zhixia Li Madhav V. Chitturi Dongxi Zheng Andrea R. Bill David A. Noyce	2013	To implement a reservation-based system in VISSIM with VISSIM’s external driver model (EDM).	Autonomous Vehicles/Traffic Operation	An autonomous control of urban traffic (ACUTA) was introduced and modelled in VISSIM. A centralized control strategy manages fully autonomous vehicles at an intersection. Once the vehicles enter the intersection manager signal controller range, they relay speed, acceleration and route information and send a reservation request. The intersection manager determines if there is a conflict and relays information back to the vehicle on when it can traverse the intersection. A mesh link network was coded in VISSIM and the occupancy of the grid by vehciles was calculated and used by ACUTA to run its reservation based system.

Table 2-1 Continued

Muhammad M. Ishaque Robert B. Noland	2005	To examine the effects of different signal timing plans on vehicular and pedestrian traffic in a microsimulation environment. To examine the trade-off between increasing pedestrian crossing time and overall vehicle delay over the entire network.	Traffic Operation	A hypothetical network is coded with two parallel streets (speed of 50 km/hr) that cross two parallel streets (30 km/hr). Pelican and Zebra crossings are also introduced in the network. There are five vehicles classes defined: passenger car, pedestrian, cab, trucks (HGV), and bus. O-D matrices for vehicles and pedestrians are defined. A number of scenarios and signal timing plans are analyzed to examine the overall multimodal delay in the network.
Ata Khan	2010	To develop a method that automatically and dynamically estimate queues and delays at border crossings.	Cross-Border Delays	A microsimulation model for the Windsor-Detroit Ambassador bridge was calibrated with traffic data. The queue and delay data from the microsimulation was used to train an aritificial neural network (ANN) model for queues an delay. The ANN was then used to predict delays and queue lengths dynamically.
Flavio Cunto Frank F. Saccomanno	2008	To calibrate and validate the simulation of vehicle safety performance at signalized intersections	Traffic Safety	A microsimulation model in VISSIM was calibrated to validate the potential of rear-end crashes at signalized intersections. The exercise consisted of four steps 1) the selection of inputs, 2) Plackett-Burnman design for screening, 3) factorial analysis for safety performance inputs, and 4) GA procedure for optaining best input values. The safety performance factors included crash potential index, number of vehicles in conflict, and total conflict. The procedure was found to be effective and closely matced observed inputs in the field.
M. Hossain	1999	To estimate the capacity of traffic circles under mixed traffic conditions using micro-simulation technique.	Traffic Operation	A coordinate approach for a microsimulation model was adapted for this research. The model was used to study and estimate the capacity for a roundabout under mixed traffic conditions in developing cities. The flow, witdth, size of roundabout annd traffic composition are important aspects when estimating the entry approach for a roundabout. A regression equation was also developed using the microsimulation results.
V. Thamizh Arasan, Shriniwas S. Arkatkar	2010	A Microsimulation Study of Effect of Volume and Road Width on PCU of Vehicles under Heterogeneous Traffic	Traffic Operation/Traffic Safety	The mixed traffic flow for Indian traffic was converted to PCU in this study to analyze the effect on road width. A microsimulation model in C++ was implemeted. It was determined that converting mixed traffic to PCU significantly changes traffic volume and width of roadway.

Table 2-1 Continued

JianguoYang WenDeng JinmeiWang QingfengLi ZhaoanWang	2006	To present the Modeling of pedestrians' road crossing behavior in traffic system micro-simulation in China	Traffic safety	A microsimlation model was developed in this study for pedestrian behaviour in China. There were two categories of pedestrians, law abiding and opportunisitc. A survey was conducted to determine the inputs for the model. A video extraction was also used to extract behavior data. The model was simulated in Visual C++ for the survey results as well as the video extraction. The model performed better for the survey results and had to be recalibrated for the video extraction.
Byungkyu Park Hongtu Qi	2006	A microscopic simulation model calibration and validation for freeway work zone network - a case study of VISSIM	Traffic Operation	This study presented a VISSIM microsimulation application for calibrating and validating a procedure to model a freeway work zone. The input data was collected from the field over multiple days to consider variability. The city of Covington, Virginia was used as the observation site. The procedure presented was effective in validating the data observed in the field.
Gabriel Gomes Adolf May Roberto Horowitz	2004	To present a microsimulation model of a congested freeway using VISSIM	Traffic Operation	A detailed freeway model of a 15 mile stretch of I-210 West in Pasadena, California in presnted in VISSIM. The site is complicated as it contains high-occupancy vehicle (HOV) lane, a heavily traveled freeway connector, metered on-ramps, and 3 interacting bottlenecks. The input data was collected with loop detectors as well as manual road surveys.
Byungkyu "Brian" Park Nagui M. Rouphail Jerome Sacks	2001	To present assessment of stochastic signal optimization method using microsimulation	Traffic Operation	A CORSIM model based on GA was assesed in this study for a set of nine signalized intersections. The GA was used to determine the best signal timing plans. The variability of traffic is accomodated and the demand changes are also discussed.
Cristián E. Cortés Vanessa Burgos Rodrigo Fernández	2010	To model passengers, buses and stops in traffic microsimulation	Traffic Safety	This research aims to provide guidelines for a realistic simulation of public transportation systems in a microsimulation environment. A number of approaches are discussed including the importance of transit stops, passengers and various transit vehicles with transfer options and control strategies. A number of examples are also provided.
Muhammad Moazzam Ishaque Robert B. Noland	2009	To model pedestrian and vehicle flow valibration in multimodal traffic microsimulation	Traffic Operation	An approach for modeling passengers in VISSIM is discussed in this study. The software inherently provides a peestrian model but it is not realistic enough to model behaviour. The model is calibrated with speed-flow models. The modeling of pedestrian-vehicle interaction is analyzed.

Table 2-1 Continued

Alfredo García Antonio José Torres Mario Alfonso Romero Ana Tsui Moreno	2011	to evaluate the effect of type and spacing of traffic calming devices on capacity using a traffic microsimulation study	Traffic Safety	A VISSIM microsimulation model is presented to evaluate the impacts of traffic calming. The effect of such devices on cross-town roads capacity was determined based on type and spacing of devices.
Vittorio Astarita Giuseppe Guido Vincenzo Giofré Alessandro Vitale	2011	To present a comparison between microsimulation and observational data for safety performance measures	Traffic Safety	A safety performance microsimulation model is presnted in this study. The estimation of road safety perforamance indicators was completed using video imaging processing as well as GPS tracking measurements. The microsimulation model is developed in TRITONE and is compared to observational data.
William Young Jeffery Archer	2009	To study a traffic signal Incident Reduction function	Traffic Safety	This study presents the approach of using microsimulation models to evaluate the safety impacts of and incident reduction (IR) function into a vehicle-actuated signal controller. The IR function is used in Sweden. The effects of IR were evaluated in three safety indicators: time to collision, red light violations, and required braking rates. An adapted IR function was found to improve the safety of a signalized intersection.
Aleksandar Stevanovic Jelka Stevanovic Cameron Kergaye	2013	To present the optimization of traffic signal timings based on surrogate measures of safety	Traffic Safety	An integrated approach for using VISSIM, a Surrogate Safety Assessment Model, and a GA model to reduce the risk of potential crashes. A set of 12 interstions on Glades Road in Boca Raton were used as a case study. The relationship between cycle length and vehicle conflicts was studied.

Dynamic Traffic Assignment

The basis of the dynamic traffic assignment (DTA) is derived from Wardrop's first principle: "*No driver can unilaterally reduce his/her travel costs by shifting to another route.*" (Wardrop, 1952). Each driver aims to reduce their travel cost and time on the road network. The driver can either have knowledge of his/her route by experience or acquiring traffic information. Since experienced travel time cannot be determined at the start of the journey, it is intuitive to assume that drivers may not always know the shortest path route. A static traffic assignment or user-equilibrium assignment is based on the concept that drivers always have knowledge of the shortest path between their origin and destination. The performance of each road link in terms of travel time is based on a link-time performance function that relies on link volume and capacity (Ortuzar & Willumsen, 2011). The steady-state travel time on each link is added together to determine the total travel time on each feasible route. While the static traffic assignment provides an hourly view of route performance, it is limited in its ability to present actual variations in performance at smaller time intervals. More specifically, the algorithm cannot depict detailed field conditions, such as speed-density relationships, that result in increased travel time and congestion on the network (Chiu et al., 2011). By comparison, the DTA has the capability of generating time-varying link or path flows on a simulation network (Varia & Dhingra, 2004). In practice, the DTA algorithm allows the user to define the numbers of origins and destinations and determines the shortest path via iterations. The user is also able to define a threshold level for convergence.

The DTA algorithm can be used for a variety of applications. Li et al.(2013) used an approximate DTA to simulate evacuation scenarios. The authors used traffic data from the Hurrricane Katrina evacuation in southeastern Louisina as input to an analytical DTA assignment to model the network with evacuation routes and contraflow. Varia & Dhingra (2004) used a simulation based DTA routine to model a multiple-origin multiple-destination network with signalized and unsignalized intersections. They tested two optimization methods to obtain a solution for the DTA and to validate field conditions: (1) methods of successive averages (MSA) and (2) genetic algorithm (GA). They concluded that MSA provided more realistic results than the GA optimization. Technical details pertaining to the DTA algorithm will be provided in the next chapter.

Connected Vehicles

The automotive industry has been increasingly investing in research and development (R&D) to improve the vehicles they produce and offer to consumers in the market. The purpose of such R&D activities is to equip vehicles with the necessary technological advancements to improve the efficiency of movement on road facilities. Vehicles are now being equipped with technology that allows the user to make informed decisions about their trip. In the world of increasing connectivity, drivers rely heavily on on-board technology to enhance their driving experience and reduce the occurrence of interruptions in their trips. The automotive industry has introduced vehicles that have the capability to relay information about road, weather and other unexpected conditions through on-board sensors and roadside infrastructure. Such information is communicated between vehicles (V2V) or between vehicles and infrastructure (V2I). The information is also passed on to traffic management centers and can be used to alert drivers about dangerous weather conditions, construction, and accidents among other unexpected conditions downstream. Given the infancy of such connected vehicle technology, research efforts have been focused on studying and understanding the effects that these connected vehicles may have on traffic in various settings.

The efficiency of signalized intersections can be improved using connected vehicle technology as presented by Guler et al. (2014). The authors used different penetration rates of connected vehicles in the traffic stream to improve the cycle lengths. The developed algorithm simulated the exchange of information from connected vehicles that are being discharged from intersections to equipped and unequipped vehicles in a specified radius. It was observed that as penetration rates of connected vehicles increased from 0% to 60% in the traffic stream, the average delay of the intersection was significantly reduced.

The modeling of advanced signal controllers can be implemented using connected vehicles in the traffic stream. Jin et al. (2012) presented an advanced traffic management system for connected vehicles. The proposed system consisted of vehicle agents (VA) and an Intersection Management Agent (IMA). The two agents are meant to collaborate so the IMA can arrange for the vehicle's arrival and the vehicle can plan its trajectory to avoid collisions. A dynamic reservation system is used for collaboration of the two agents. The multi-agent approach was executed in SUMO (Simulation of Urban Mobility). Lee & Park (2012) also developed an algorithm for an advanced traffic management systems known as Cooperative Vehicle Intersection Control (CVIC) system. This management CVIC allows for safe maneuver of fully automated vehicles without the use of traditional traffic lights. The algorithm is developed by manipulating vehicle trajectories and converting them to a non-linear constrained optimization problem. A recovery control algorithm is also developed to handle any overlapping trajectories or malfunctions. To further improve the traditional traffic light system, Goodall et al. (2016) developed an algorithm that collects vehicle information and allows traffic control systems to respond to real-time traffic demands eliminating the manual update of signal timing plans. A Predictive Microscopic Simulation Algorithm (PMSA) was developed where vehicle delay information is collected, and an objective function is optimized using the rolling horizon method. The model was populated with delay information and was simulated on a test network along Route 50 in Chantilly, Virginia.

The improvement of transit management is also a possibility with the presence of connected vehicles in the traffic stream. The existing Transit Signal Priority (TSP) systems commonly used to manage transit systems run on models that can cause inaccuracy in predicting transit arrival times and result in network delays and queues. Hu et al. (2014) developed a TSP model that allows two-way communication between buses and traffic signal controllers. During the cycle length, green time is ‘moved’ to the phase where it is needed, rather than added, to increase efficiency.

Research efforts have also been made to determine if information collected from connected vehicles can be used for queue detection and congestion mitigation. Tiaprasert et al. (2015) developed a mathematical model for queue length estimation using connected vehicle technology without the traffic volume, queue characteristics and signal timing information. The queue length estimation algorithm was designed so various queue conditions could be modelled. The Discrete Wavelet Transform (DWR) method was used to detect and correct queue estimation errors. The algorithm was tested on an isolated intersection model in VISSIM. Christofa et al. (2013) also developed a queue spillback detection method using data collected from connected vehicles in the traffic stream. They also discussed an alternative signal control strategy with vehicle metering at critical intersections to aid in the mitigation of queues. The proposed signal control method and queue spillback detection was tested on a four-signal segment of San Pablo Avenue in Berkeley, California.

The impacts of connected vehicle technology on other aspects such as safety and emissions were also examined in recent years. Olia et al. (2016) presented a comprehensive microsimulation model for the assessment of mobility, emission, and safety measure using the microscopic traffic simulation software Paramics. There are two vehicle types defined in the study: uninformed and non-connected (non-CV), informed and non-connected (non-CV), and connected (CV). The Paramic simulation software was used with an integrated algorithm that was developed by the authors. The model was coded so the connected vehicles would have randomized levels of awareness and driving behavior aggressiveness. Incidents were modelled to determine the response of both connected and non-connected vehicles. Time-to-collision (TTC) was calculated from Paramics data to determine traffic safety. The Comprehensive Modal Emissions Model (CMEM) was integrated in the Paramics model to estimate vehicular emissions. The model was applied for a road network in north of Toronto, Canada and demonstrated lane closures, construction, and heavy congestion.

There is little information available in the literature regarding the influence of connected vehicle technology on cross-border traffic movement. Since land border corssings play a vital role to Canada’s economic stability, there is a great need for information and technology to improve the movement of cross-border traffic movement. This research project aims to fill this gap with a region-wide microscopic traffic simulation model that analyze freight truck movement between Ontario and key destinations in the

U.S. The project also aims to examine how connected vehile technology onboard commercial trucks crossing between Canada and the U.S. can impact the performance of freight movement at the border under different market penetraion rates. A summary of the research efforts is presented in Table 2-2.

Table 2-2 Literature Summary for Connected Vehicles

Author(s)	**Year**	**Objective**	**Methodology Overview**
Alireza Talebpour Hani S. Mahmassani	2016	To present a model that diffrentiates between connected and autonomous vehicles and uses appropriate assumptions for the different communication methods of such vehicles.	The difference between conventional, connected and autonomous vehicles was defined. An acceleration framework is developed that captures the complex driving environment in mixed traffic stream. A number of vehicle communication models are developed and presented. A stability analysis of the traffic, with homogenous and heterogenous vehicle types, is also performed under this framework.
S. Ilgin Guler Monica Menendez Linus Meier	2014	To present an algorithm that collects intersection departure information from connected vehicles. To use the developed algorithm to analyze the value of autonomous vehicle control and detailed vehicle information.	An algorithm was developed using MATLAB. It evaluates the use of connected vehicle technology in traffic management. A basic intersection of two one-way street was used to test the algorithm. The goal of this algorithm was to minimize total delay or total number of stops. Once the vehicle entered the controller's detectrion range, the arrival time and the distance to intersection was recorded. The algorithm was then tested for fully autonomous vehicle and connected vehicles.
Eleni Christofa Juan Argote Alexander Skabardonis	2013	To present two queue spillback detection methods based on connected vehicle data. The study also present an alternative signal control strategy to mitigate queue spillbacks when they were detected.	The ideal queue threshold estimation is defined. There are two spillback detection methods used: a gap-based method and a shockwave-based method. An alternative signal control strategy is proposed where vehcile are metered at the intersection upstream of the critical intersection. The proposed signal control method and queue spillback detection was tested on a four-signal segment of San Pablo Avenue in Berkely, California.
Qiu Jin Guoyuan Wu Kanok Boriboonsomsin Matthew Barth	2012	To develop and evaluate the time-space reservation techniques of connceted vehicle.	An advanced traffic management system for connected vehicles is proposed consisting of vehicle agents (VA) and an Intersection Management Agent (IMA). The two agents are meant to collaborate so the IMA can arrange for the vehicle's arrival and the vehicle can plan its trajectory to avoid collisions. A dynamic reservation system is used for collaboration of the two agents. The multi-agent approach was executed in SUMO (Simulation of Urban Mobility)

Table 2-2 Continued

Arash Olia Hossam Abdelgawad Baher Abdulhai Saiedeh N. Razavi	2016	To present a microsimulation model for the assessment of mobility, emission, and safety measure using Paramics. A case study is also presented to demonstrate the impacts of connected vehicles on mobility, emissions and safety measures.	There are two vehicle types defined in the study: uninformed and non-connected (non-CV), informed and non-connected (non-CV), and connected (CV). The Paramic simulation software was used with an integrated algorithm that was developed by the authors. The model was coded so the connected vehicles would have randomized levels of awareness and agressiveness. Incidents were modelled to determine the response of both connected and non-connected vehicles. Time-to-collision (TTC) was calculated from Paramics data to determine traffic saftey. The Comprehensive Modal Emissions Model (CMEM) was integrated in the Paramics model to estimate emissions. The case study area was for a road network in north of Toronto, Canada and demonstrated lane closures, construction, and heavy congestion.
Joyoung Lee Byungkyu Park	2012	To develop and evaluate an algorithm for a Cooperative Vehicle Intersection Control (CVIC) system that allows for safe maneuver of fully automated vehicles without the use of traditional traffic lights.	The algorithm is developed by manipulating vehicle trajectories and converting them to a non-linear constrained optimization problem. A recovery control algorithm is also developed to handle any overlapping trajectories or malfunctions. The model assumes 100% penetration rate of connected vehicles in the traffic stream and that all vehicles are able to communicate with the signal controller at the intersection. The study only model passenger vehicles, other vehicle types are not considered.
Kamonthep Tiaprasert Yulong Zhang Xiubin Bruce Wang Xiaosi Zeng	2015	To present a mathematical model for queue length estimation using connected vehicle technology without the traffic volume, queue characteristics and signal timing information.	An algorithm was designed to adapt to fixed-time and actuated signals. The model assumed that penetration ratio of connected vehicles would be known, the probability of each vehicle being detected is equal, and individual speed and location information of vehicles could be collected. The queue lenth estimation algorithm was designed so various queue conditions could be modelled. The Discrete Wavelet Transform (DWR) method was used to detect and correct queue estimation errors. The algorithm was tested on an isolated intersection model in VISSIM.

Table 2-2 Continued

Noah Goodall Biran L. Smith Byungkyu (Brian) Park	2013	To present a traffic control algorithm that incorporates the rolling horizon method to optimize delay or a combination of delay, stops, and deceleration. The algorithm is responsive to vehicle demands and used connected vehicles and wireless sensors to collect information.	The authors callled the algorithm a predictive microscopic simulation algorithm (PMSA) to improve current traffic control systems and respond to real-time traffic demands eliminating the manual updating of signal timing plans. The algorithm was developed by collecting vehicle delay information from a microsimulation model of an intersection with an acyclic traffic signal. A rolling horizon approach was used to optimize the objective function. Once the PMSA model was populated with the delay information, a test network along Route 50 in Chantilly, Virginia was simulated.
Jia Hu Byungkyu (Brian) Park A. Emily Parkany	2014	To present an improved Transit Signal Priority (TSP) logic with the use of connected vehicle technology and traffic signal controllers.	According to the authors, existing TSP systems run on models that can cause inaccuracy in predicting the bus arrival times and cause adverse effects on the road network. The developed TSP model allowed for two-way communication between buses and traffic signal controllers. The model moved green time to the phase where it was needed instead of adding green time, thereby keeping the cycle length the same.

3. METHODS OF ANALYSIS

Study Area

The scope of this project is to analyze freight truck movement between Ontario and key destinations in the U.S. via the Windsor and Sarnia land-border crossings. As noted in Chapter 1, these two land borders account for the majority of truck traffic between Ontario and the U.S. The two crossings are located in southwestern Ontario Canada. Traffic moving through the Blue Water Bridge via Sarnia, Canada is facilitated by Highway 402, while traffic moving through the Ambassador Bridge via Windsor is facilitated by Highway 401. Figure 3-1 highlights the two international land border crossings and the location of the analyzed origin-destination pairs. As the map shows, the analysis considers traffic moving on Highway 401 from a point in proximity to Woodstock, Ontario. This point represents traffic moving on Highway 401 from the Greater Toronto Area (GTA) in Ontario before splitting to either go on Highway 402 towards the Blue Water Bridge or continuing on Highway 401 towards the Ambassador Bridge. The distances between Woodstock and the Blue Water Bridge is approximately 150 km, while it is 230 km in the case of the Ambassador Bridge. The chosen U.S. destinations include Chicago, IL, one of the largest transportation hubs in North America, as well as Toledo, OH, where a large percentage of trucks travel.

Figure 3-1 Study Area

Modeling Approach

Dynamic Traffic Assignment (DTA) Framework

A dynamic traffic assignment algorithm is an extension of the standard traffic assignment problem. The goal of the DTA model is to determine the pattern of traffic flow over the horizon period by identifying the shortest or ‘best’ path between the analyzed OD pairs. Figure 3-2 describes a general traffic simulation flow chart. The traffic demand (represented by the OD pairs) and the traffic network (represented by road links) are combined with the route choice model and then added to the simulation model.

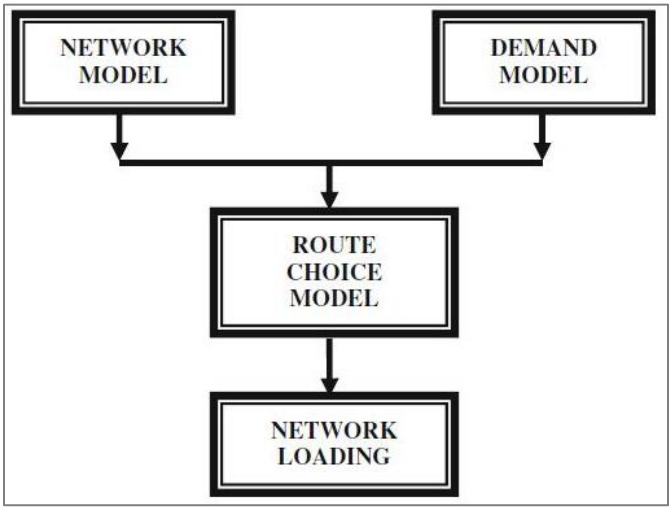


Figure 3-2 Conceptual Approach to a Dynamic Transportation Model; Source: (Barceló, 2010)

To model realistic field conditions, the simulation model needs to be able to replicate these conditions using the software. The standard static traffic assignment assumes that traffic flows and associated conditions are in equilibrium in a large time interval (e.g., one hour). By comparison, the DTA models try to overcome the static nature by modeling traffic in small time varying intervals (e.g. 1 minute or 15 minutes). As in the case of the static assignment, the DTA solution is achieved through an iterative procedure that checked for stability in traffic conditions. The latter is the outcome of traveler's route choice, which is influenced by network congestion. Congestion itself is driven by the route choice and the progression of vehicles that depart the origins at different times in the simulation. The iterative procedure begins the process with an initial set of routes (normally shortest paths based on some sort of cost such as distance) and the procedure updates the routes in each iteration until convergence is reached. Convergence is achieved when traffic conditions become stable (i.e. traffic reaches equilibrium). Technically, the procedure checks for what is known as User Equilibrium (UE) conditions in each iteration. UE occurs when no driver on the network can benefit from unilaterally changing their route choice on the network. As such, at UE the travel time on all used paths is less than or equal to the travel time on all un-used paths (Sheffi, 1985). If the network is large, the iterations can continue for a long time. However, the convergence is generally user-defined to allow the model to reach a stable condition in a reasonable amount of time (Chiu, et al., 2011).

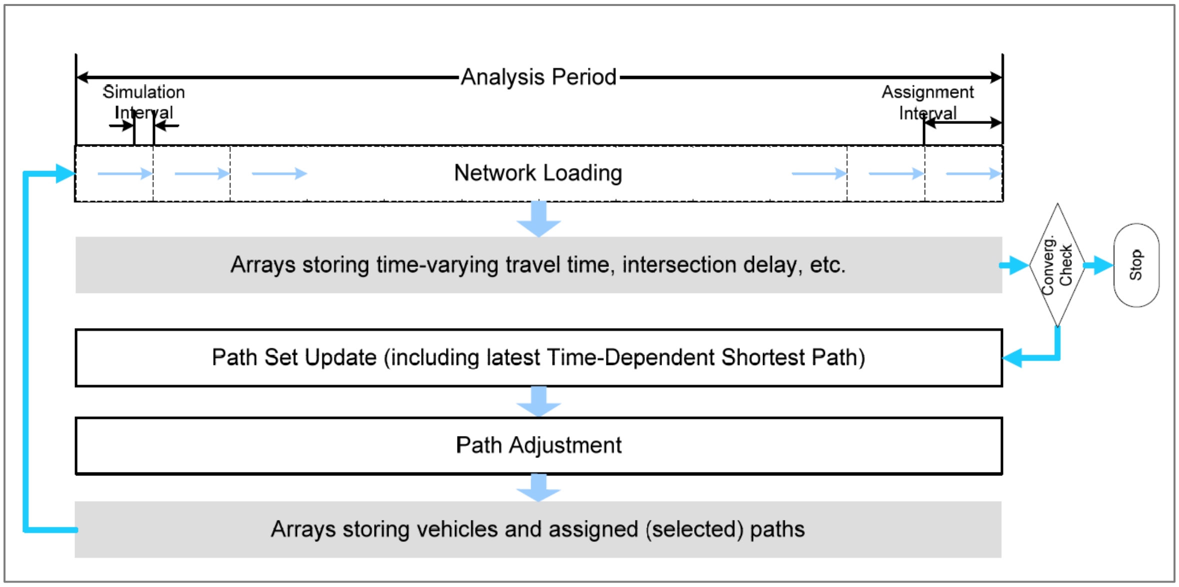


Figure 3-3 General DTA Algorithmic Procedure; Source Chiu, et al. (2011)

Figure 3-3 describes a general algorithmic procedure that most simulators follow to arrive at the set converged solutions. As reported by Chiu et al. (2011), the following three criteria are applied in sequence until a satisfactory solution is reached:

1. Network Loading: Given a set of route choices, what are the resulting travel times?
2. Path set update: Given the current path travel times, what are the new shortest routes (per OD pair and departure time-interval)
3. Path assignment adjustment: Given the updated route sets, how vehicles (or flows) should be assigned to routes to better approximate dynamic user equilibrium.

DTA models differ in how each step is implemented. The network loading process differs from an analytical model to a simulation model. The second step (i.e., the path set update) analyzes the results of the network loading step. The paths with high costs and/or low traffic volume are used less in the next iteration until a stable condition is reached. The next step continues the path adjustment from the traveler’s route choices. The algorithm repeats until the user-defined convergence value is reached.

VISSIM

VISSIM is a microscopic simulation software that models multimodal traffic operations. The quality of the simulation is based on the traffic flow model that the software is based on. VISSIM uses a psycho-physical model developed by Wiedemann in 1974. The software has the capability of replicating realistic conditions such as road capacity, speed changes, design of simple and complex intersections, and traffic volume. It also generates several validation measures such as travel time between two points, traffic queues at specified locations, delays in the network, and levels of service (PTV Group, 2017).

Dynamic Traffic Assignment

VISSIM has the capability of performing a dynamic traffic assignment (DTA). Figure 3-4 outlines the steps that the DTA module in VISSIM goes through when running simulations. As shown, the DTA is an iterative procedure that uses Origin-Destination information as key input. The algorithm allows the analyst to set the type of cost to use in the calculation along with the convergence criteria and maximum number of iterations. In the first iteration, the algorithm starts by determining the shortest routes connecting the origins to the destinations based on distance. Next, the algorithm will start simulating the movement of individual vehicles (i.e., performing a microsimulation) using the built-in psycho-physical model of VISSIM to determine the travel cost on each used path. Here, the DTA in VISSIM determines all possible paths in the network and distributes traffic on these paths. The path selection decision is based on a discrete choice model. Intuitively, not all drivers are aware of the ‘best’ path in the network. Therefore, the DTA module starts by distributing the traffic on each path to determine travel time and cost. Next, the procedure employs the Method of Successive Averages (MSA) to calculate travel time for the current iteration. This is achieved using the following formula:

$$t_l^n = t_l^{n-1} + \alpha_n \cdot (y_l^n - t_l^{n-1}) \qquad \ldots(1)$$

Where:

y_l^n = experienced travel time on link *l* in iteration *n*

t_l^n = smoothed travel time on link *l* in iteration *n*

t_l^{n-1} = smoothed travel time on link *l* in previous iteration *n-1*

The travel time from each preceding iteration is given the same weight as the current one. That is, α_n is represented as the arithmetic mean of all iterations to calculate the smoothed travel time on link *l* for iteration *n*. The use of the arithmetic mean reduces the influence of further iterations on the path selection process. The smoothing factor α_n for iteration *n* is calculated as follows:

$$\alpha_n = \frac{1}{N+n} \qquad \ldots(2)$$

Where *N* is the total number of iterations set by the user. Once the new travel time y_l^n for iteration *n* is calculated for link *l*, the smoothed travel time is calculated as the weighted sum using equation (1). The smoothed travel time for iteration n is then used in the next iteration to determine the ‘best’ paths between a specific origin-destination pair. The traffic assignment undergoes a specified number of iterations until it converges. Convergence is achieved when y_l^n is equal to t_l^{n-1}. At such point, the paths representing the UE conditions will be used by the vehicles to go from the defined origins to destinations.

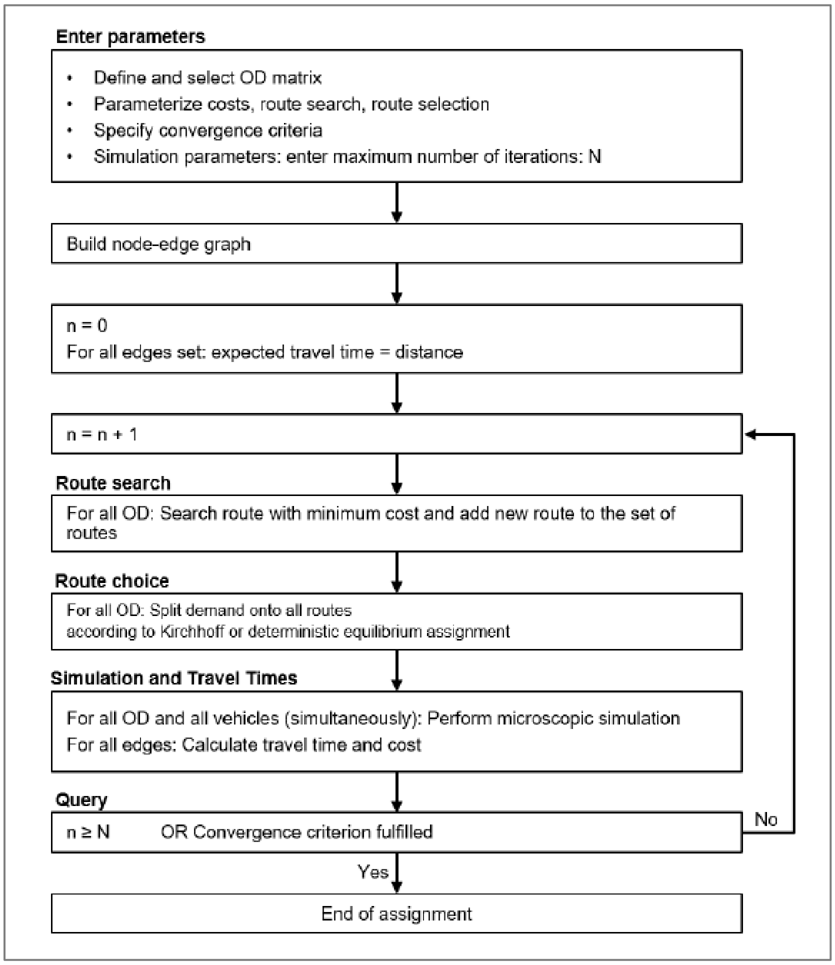


Figure 3-4 VISSIM Dynamic Traffic Assignment Flow Diagram; Source: PTV America 2018

Calculating Paths and Costs

Paths in VISSIM are a compilation of links on which vehicles travel during the simulation. A path begins at the origin parking lot and ends at a destination parking lot. The path selection is done based on generalized costs of the path. The cost consists of travel time, distance and link costs of the paths. The user has the following three options for the path selection algorithm:

- Volume (Old): The path search is exclusively based on volumes of previous simulation runs.
- Stochastic Assignment (Kirchhoff): The traffic is assigned in each iteration based on the generalized costs of the previous iterations. The assignment results in the following:
    - Low cost paths have high traffic volume
    - High cost paths have low traffic volume
    - Paths with identical costs have identical traffic volume
- Equilibrium Assignment: The traffic demand is proportionally distributed on the paths.

Since there are multiple paths between the origin and destination parking lots, VISSIM must also model the driver decision to take a specific path.

In the DTA module of VISSIM, the path selection is performed using either the sum of link travel times or the measured path travel times according to a stochastic assignment. In the latter, path selection is based on a discrete choice model since the driver will be faced with choosing a path like R from a discrete set of alternative paths {1, 2, 3, …, j}. The selection is done using generalized cost generated from expected travel time, distance or financial costs for the edges in the network.

The generalized cost is defined as follows:

$$C_R = \sum_{l \in R} C_l \qquad \ldots (3)$$

Where:

C = generalized cost

R = a path

l = a link that occurs in path R

The stochastic path selection algorithm assumes that not all drivers are aware of the best path between an OD pair. The algorithm distributes traffic on all possible routes and the generalized cost is used to determine the shortest path between the OD pair. The cost information is collected in each iteration and the search for the shortest route keeps repeating until convergence is reached. If there are unused paths, VISSIM automatically assigns a 0.1s time to such paths. The cost for each path is different and is offset by the benefit provided by this path. The utility provided by each path is formulated as the reciprocal of the generalized cost in the discrete choice model. Here, the utility is given as follows:

$$U_j = \mu \frac{1}{C_j} \qquad \ldots (4)$$

Where:

U_j = the benefit of path j

C_j = the generalized costs of path j

μ = sensitivity parameter reflecting the choice behavior based on the perceived travel time. The value of the sensitivity parameter influences the decision behavior of the drivers. A low value would result in a distribution where the utility has little to no effect on the driver behavior. A high value would result in all drivers choosing the shortest path.

The decision behavior is modelled using the multinomial logit model which is defined as follows:

$$P(R) = \frac{\exp(U_R)}{\sum_j \exp(U_j)} \qquad \ldots (5)$$

Where:

U_j = the utility (i.e., benefit) of choosing path *j*

$P(R)$ = the probability of selecting path *R*

The logit model is translationally invariant and therefore only considers the absolute difference of benefits. If the cost function as described above, is the only factor in the logit probability, the model applies the same importance to travel time difference of 5 and 10 minutes and 105 and 110 minutes. Since the two differences are perceived significantly different, the model needs to be able to realistically differentiate between them. To ensure that the model is able to differentiate between the two differences realistically, the cost function described above cannot be used with the logit function. To ensure a realistic distribution, the logit formulation is changed to the following in VISSIM:

$$P(R) = \frac{U_R}{\sum_j U_j} \qquad \ldots (6)$$

The sensitivity parameter here determines how the model responds to differences in benefits. The model is able to use ratio of benefits to determine the distribution and not the absolute difference of benefits. Therefore, there would be slight traffic variation in the paths of 105 minutes and 110 minutes, whereas the path with a 5-minute travel time would be more popular than the 10 minute one.

DTA Road Networking Coding in VISSIM

In order to simulate traffic, the model of the road network needs to be replicated in the traffic simulator. The dynamic traffic assignment requires less detail as the network size is generally quite extensive. Since the point of the network is to use a traffic assignment, the microscopic details do not play an important role. It also uses network elements in a different context than a standard simulation. This section details the steps taken to code the road network into VISSIM so that the dynamic traffic analysis could be undertaken.

Links and Connectors

The basic elements in a VISSIM road network are links and connectors. Links can be created in one direction over multiple lanes. Connectors are used to join links that may run in different direction such as turning movements. Links and connectors are independent elements that can be created by themselves in VISSIM. They provide a base for dependent elements such as speed decisions, route assignments, and parking lots. There are two ways to visualize the VISSIM road network. Figure 3-5 and Figure 3-6 present the road network with the wireframe display disabled and enabled, respectively.

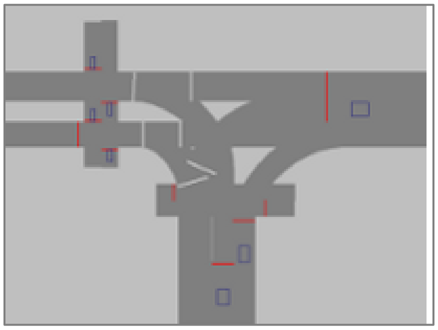


Figure 3-5 VISSIM Road Network Example - Wireframe Mode Disabled

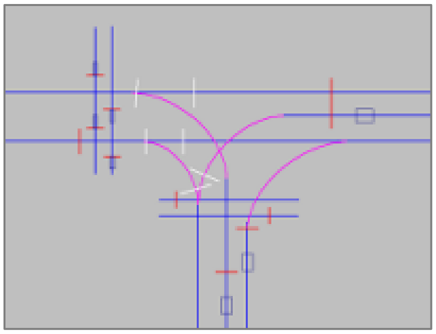


Figure 3-6 VISSIM Road Network Example: Links (Blue) and Connectors (Pink) - Wireframe Mode Enabled

Defining Origin-Destination Zones

The DTA module in VISSIM requires the user to define origin-destination (OD) pairs. The following network elements are used to define OD pairs for the simulations in the software.

Nodes

Nodes are generally used for evaluation purposes in VISSIM. They are created around an intersection to determine LOS, queue, throughput and such. These nodes can also be used for dynamic traffic assignment. The nodes must be placed at network boundaries for dynamic traffic assignment zone creation. Figure 3-7 highlights the required placement of the nodes.

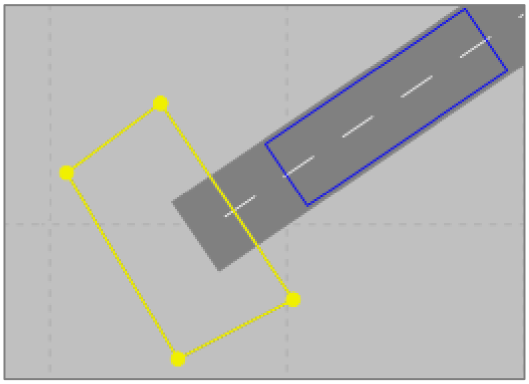


Figure 3-7 Node placed at the edge of a Link in VISSIM for the DTA module

Edges

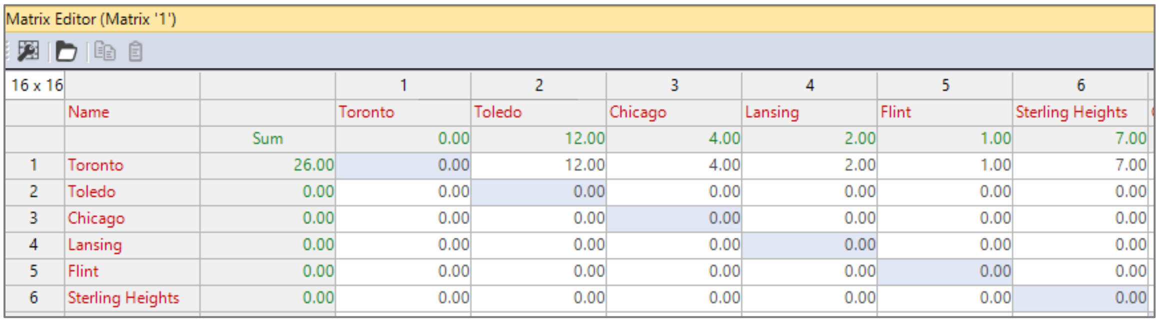
Links and connectors between nodes are considered an edge. These edges are the basis for path search in the DTA module. Travel time, distance and cost are measured and recorded for these edges and used in the next iteration for best path selection.

Parking Lots

The DTA module uses parking lots as zone connectors. Once the nodes have been created at the boundaries of the network, the parking lot feature is used to define a specific OD pair.

Origin Destination Matrices

Origin-Destination (OD) matrices are used in the DTA module to assign traffic volume in a specific time period. The ability to define volume and vehicle composition for specific times of day such as peak and off-peak hours allows the user to realistically simulate traffic flow on the network. Figure 3-8 shows the Matrix Editor in VISSIM.



Matrix Editor (Matrix '1')

16 x 16			1	2	3	4	5	6
	Name		Toronto	Toledo	Chicago	Lansing	Flint	Sterling Heights
		Sum	0.00	12.00	4.00	2.00	1.00	7.00
1	Toronto	26.00	0.00	12.00	4.00	2.00	1.00	7.00
2	Toledo	0.00	0.00	0.00	0.00	0.00	0.00	0.00
3	Chicago	0.00	0.00	0.00	0.00	0.00	0.00	0.00
4	Lansing	0.00	0.00	0.00	0.00	0.00	0.00	0.00
5	Flint	0.00	0.00	0.00	0.00	0.00	0.00	0.00
6	Sterling Heights	0.00	0.00	0.00	0.00	0.00	0.00	0.00

Figure 3-8 Origin-Destination Matrix Editor Window in VISSIM

Trip Chain Files

Traffic demand can also be modeled with trip chain files in the DTA module. These files contain detailed information about trips for individual vehicles. A trip chain can be made up of multiple trips. The trip chain file consists of the following information:

- Number of the vehicle
- Type of vehicle
- Origin zone number
- Departure time
- Destination zone number
- Minimum dwell time.

The trip chain files used for the various phases are presented in APPENDIX A:.

Vehicle Types

To model the traffic conditions as required for this study, the following vehicle types were introduced:

- HGV: Regular trucks
- HGV with C2X (no message): Connected trucks with no active message
- HGV with C2X (active message): Connected trucks with active message
- FAST class HGV: FAST class designated trucks
- Car: Passenger Vehicles

Connected Vehicles

One of the goals of the research project in this thesis is to examine the effects of connected vehicles on the performance of international border crossing facilities. Previous studies introduced connected vehicles into the traffic stream at different penetration rates (Guler et al. (2014); Talebpour & Mahmassani (2016)). In this thesis, we will follow a similar approach to examine the effects of having various levels of connected commercial trucks in the traffic stream moving between southwestern Ontario and the U.S. To handle connected vehicles in simulations, an integrated python script running under the Component Object Model (COM) of VISSIM 10.0 is utilized.

V2X Python Code

The Python program used in the simulation is based on an existing script provided in the file “Car2X Script.py” under the examples training folder of PTV VISSIM 10.0. The script was modified to function with the dynamic traffic assignment. The modified code is presented in APPENDIX B:. The V2X code works by first directing one vehicle towards a parking lot to imitate the occurrence of an incident. The user defines the location of the parking lot (i.e. ‘incident’ location) before the simulation begins. Once the vehicle is detected in the parking lot, the code triggers the start of communication between the disabled vehicle (at the parking lot) and the connected vehicles upstream. The communication within the microsimulation is based on a cumulative distance distribution (see Figure 3-18 and Figure 3-20 later in this chapter) that the user defines before initiating the simulations. Vehicles receiving the message have then a choice of avoiding the incident by either changing lanes or using another path to travel to the destination.

User-Defined Attributes

For the Python code to model the communication between vehicles, the attributes of connected vehicles were defined manually in the VISSIM model. The integration of these attributes was necessary as vehicles do not have this capability in VISSIM 10.0.

The attributes are defined as follows:

- C2X_HasCurrentMessage: Vehicles that are receiving the message.
- C2X_MessageOrigin: The coordinates where the incident occurs, and the message is sent out
- C2X_Message: The text of the message being sent out
- C2X_DesSpeedOld: The value of the vehicle speeds before the incident occurs
- C2X_SendingMessage: Vehicle that is transmitting the message
- C2X_Status: the status of all vehicles
    - 0: Vehicle has no C2X equipment
    - 1: Vehicle has no active C2X message
    - 2: Vehicle receiving the message
    - 3: Vehicle transmitting the message

Demo Connected Vehicles Scenarios in VISSIM's DTA

While our tests will focus on the movement of connected vehicle on the real network presented in Figure 3-1, we started by testing the functionality of the connected vehicles python code in a DTA context in VISSIM with the help of a simplified demo network. The network consisted of 3 paths, two of which had the same capacity and a third alternative route for vehicles to use when avoiding the presence of a traffic incident. The network is presented in Figure 3-9. There were three test scenarios that were modelled on this network. The first test scenario modelled traffic on a base network without an incident or connected vehicles to evaluate the functionality of the DTA as well as establish a benchmark travel time and traffic pattern. The second scenario modelled an incident without connected vehicles in the traffic stream. The third test scenario modelled an incident with the presence of connected vehicle technology to examine the effect of such technology on the traffic patterns when a traffic incident is present.

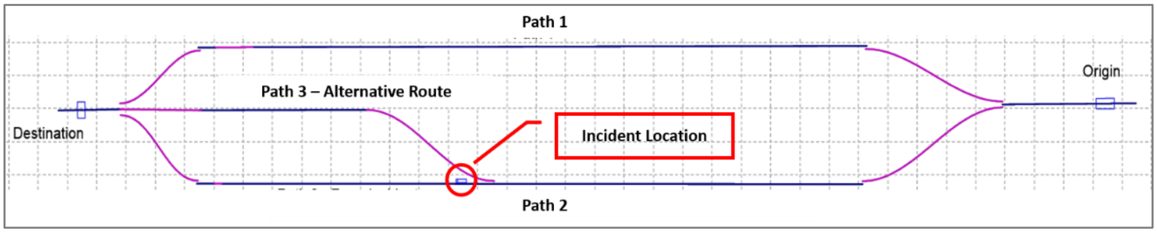


Figure 3-9 Demo Network

Simulation Parameters

The tested simulations were set to run for a maximum of 25 iterations with a convergence criterion of 95% of travel time of the previous run for 5 consecutive runs.

Data Sources

The microsimulation model requires OD matrices for passenger vehicles and commercial trucks between the GTA region and key destinations in the U.S. via the Ambassador Bridge and Blue Water Bridge. There are a number of datasets that will be used to generate the matrices during the course of this research to model the dynamic traffic assignment and route choice modelling in VISSIM.

Commercial Vehicle Survey Data

The Ministry of Transportation of Ontario (MTO) collects traffic count data from traffic count stations in each of its 49 Census Division (CD). If a CD does not have a station located in it, the nearest station is assigned to it. The hourly truck trips are determined from the traffic count data. An hourly distribution is created by averaging the hourly truck trips in each CD. Hourly factors for 24 hours are applied to devise a daily OD matrix. The daily truck flows were determined using the method described above for the 49 Census Divisions of Ontario from the 2012 MTO Commercial Vehicle Survey (CVS). The trips for external zones (border crossings) were determined the same way as the internal zones (Census Divisions). The CVS provides information on the volume of border crossings traffic. The data for Ambassador Bridge and Blue Water Bridge was filtered out to determine the daily truck count on the two border crossings. Figure 3-10 provides the share of traffic moving through the two border crossings based on the CVS data.

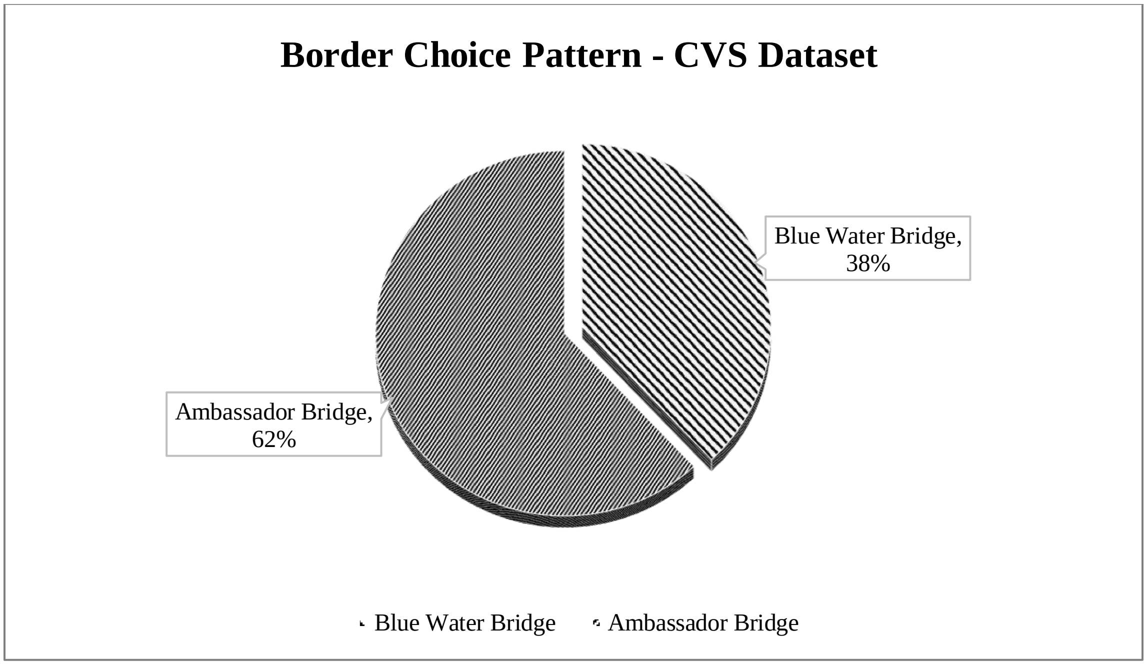


Figure 3-10 Border Choice Pattern extracted from the CVS Dataset

RTMS Data

Remote Traffic Microwave Sensor (RTMS) dataset is created with vehicle information collected with units owned by the Cross-Border Institute (CBI) of the University of Windsor. The units sense all the lanes on the Huron Church Rd. near the approach leading to the Ambassador Bridge to record the length of the vehicle to characterize them. This data is collected for a day in April 2016, in 1-minute intervals and was used to develop OD matrices in 15-minute intervals for the analysis.

BTOA Data

The Bridge and Tunnel Operators Association is a "*binational membership organization representing the international bridge and tunnel crossings between the Province of Ontario and the States of Michigan and New York*" (BTOA, 2019). The member organizations facilitate and collect data about the movement of goods between Canada and the U.S. The data includes monthly traffic volume statistics for border crossings between Ontario and the States of Michigan and New York. The data extracted from the BTOA data was for April 2016 and is presented in Figure 3-11.

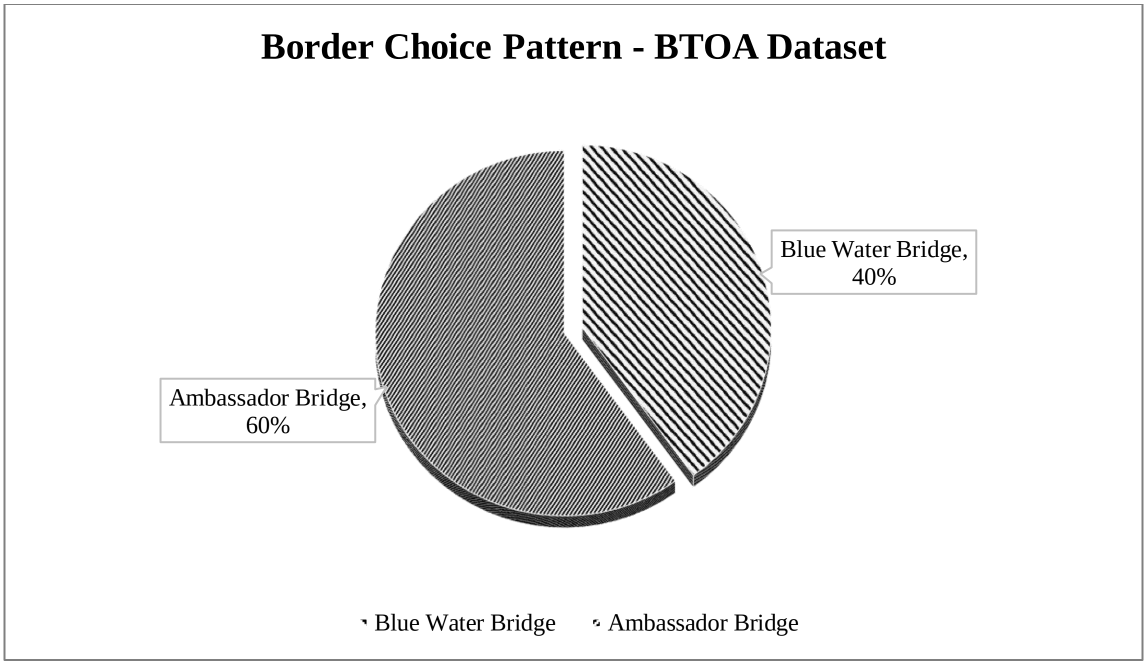


Figure 3-11 Border Choice Pattern extracted from the BTOA dataset

Passive GPS Data

Transport Canada acquired GPS data from Shaw Tracking, a telecommunication company that allows Canadian freight companies to track their fleet in real time. The raw data is in the form of GPS 'pings' that contain a time stamp, truck ID, carrier, and longitude and latitude coordinates of the truck when it 'pinged' on the network. The carrier information is kept anonymous for confidentiality purposes. The analysis year was 2013 and the data was available on a monthly basis. This dataset, temporarily provided by Transport Canada, was used by Gingerich et al. (2016) to map the truck trips for cross-border movement between Canada and the U.S. The dataset was used in this research to determine key destination locations in the United States and traffic distribution on the road network being modeled as well. The border choice pattern is presented in Figure 3-12.

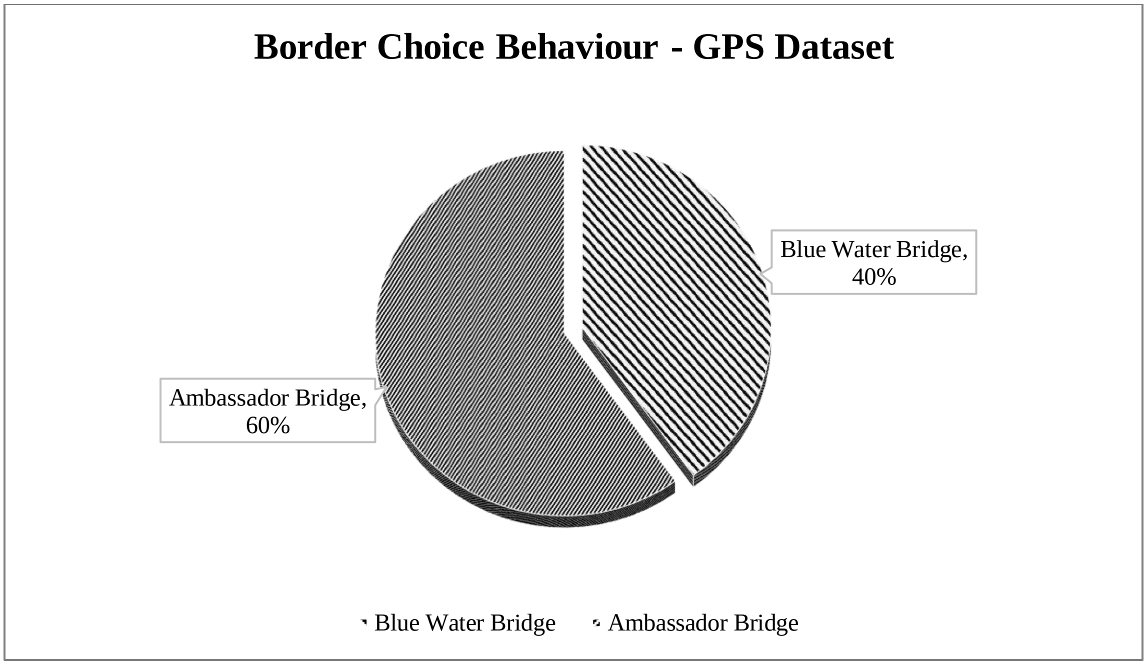


Figure 3-12 Border Choice Pattern extracted from the GPS dataset

Development of OD Matrices

The VISSIM model requires OD matrices to run the DTA module and find the shortest paths in the network. To model a realistic daily traffic simulation, time is divided into 15-minute intervals to create OD matrices at this temporal level for the VISSIM model. There were two main vehicle classes used for the simulation. The following sub-sections outline the processes used to create the OD matrices for each vehicle type.

Freight Trucks

Since heavy freight trucks are the focus of this study, tremendous care was taken to develop the OD matrices to ensure that the model was as realistic as possible. There were a number of datasets used to determine and validate the total number of trucks crossing the border on a weekday. It was reported in the CVS dataset that a little over 5000 trucks crossed the Ambassador Bridge and almost 3000 trucks crossed the Blue Water Bridge. An hourly breakdown of the crossing volume was also provided which was used to determine the crossing percentage of trucks at each crossing. To ensure that the crossing volume was cross-validated, the BTOA and the RTMS datasets were also utilized. It was determined that 60% of truck volume is processed at the Ambassador Bridge and 40% of the volume is processed at the Blue Water Bridge. Since the RTMS dataset is only available for Ambassador Bridge, the crossing volume was validated against the other datasets for accuracy. The following list outlines the steps taken to develop truck OD matrices for 15-minute intervals and the corresponding tables are presented in APPENDIX C:.

1. A weekday was selected in the RTMS dataset and vehicle count was available on a minute-by-minute basis. The data was combined to find totals for 15-minute intervals for a 24-hour period, as presented in Table C-1 and Table C-2.
2. The percentage of total volume for each destination was determined from the GPS dataset. This percentage was multiplied by the total number of trucks, determined from the RTMS dataset, Table C-3, to calculate the arrival rate for each 15-minute interval.
3. The hourly truck trips were then divided by the total hourly volume to calculate the crossing breakdown of each hour. Since RTMS data was only available for the Ambassador Bridge, the breakdown of each hour was necessary to calculate the arrival rate at both bridges, as presented in Table C-5 and Table C-6.
4. The hourly breakdown was then multiplied by the hourly total from the CVS dataset to calculate volume for each 15-minute interval for both bridges, as presented in Table C-7 and Table C-8.

5. Since each dataset provides traffic count at the border crossings, and the traffic was being introduced at Woodstock, ON, the matrices were introduced at an earlier hour for realistic arrival conditions.
    a. Since each matrix represented a 15-minute interval, both border crossings were adjusted according to the travel time between Woodstock ON and the border crossing.
    b. For instance, it takes 2 hours and 15 minutes to reach the Ambassador Bridge from Woodstock ON. The traffic was introduced in a manner that ensured that the traffic arrival data matched the field data.
6. The matrices were then organized in a standard origin-destination format to be implemented in the VISSIM model, as presented in Table C-11.

Passenger Vehicles

Passenger vehicles were introduced in the model for realistic traffic conditions at the border crossings. The GPS dataset only provides information about trucks, therefore the RTMS, CVS and BTOA datasets were used. Since international truck traffic passes through Windsor, Ontario on the Huron Church Road to reach the Ambassador Bridge, local traffic was also modeled using the City of Windsor's AADT. The following list outlines the steps taken to develop truck OD matrices for 15-minute intervals. The passenger vehicle data was extracted from the same time period as the freight trucks.

1. A weekday was selected in the RTMS dataset and vehicle count was available on a minute-by-minute basis. The data was combined to find totals for 15-minute intervals for a 24-hour period.

2. The traffic volume for passenger vehicles was equally divided for the destinations as they were introduced to represent background traffic and weren't the focus of the analysis. The percentage of total volume for each destination was determined from the GPS dataset. This percentage was multiplied by the total number of cars, determined from the RTMS dataset, Table C-4, to calculate the arrival rate for each 15-minute interval.
3. The hourly trips were then divided by the total hourly volume to calculate the crossing breakdown of each hour. Since RTMS data was only available for the Ambassador Bridge, the breakdown of each hour was necessary to calculate the arrival rate at both bridges.
4. The hourly breakdown was then multiplied by the hourly total from the CVS dataset to calculate volume for each 15-minute interval for both bridges, as presented in Table C-9 and Table C-10.
5. The matrices were adjusted to be introduced at an earlier hour, so the traffic count matches the data from the field.
6. The matrices were then organized in a standard origin-destination format to be implemented in the VISSIM model, as presented in Table C-12.

Border Clearance Time Distribution

The objective of this study was to model a realistic border crossing scenario which required processing times for both bridges. Gingerich et al. (2016) assessed these times in their study and this data was used to develop the time distributions for the Ambassador Bridge and the Blue Water Bridge. The times reported in Figure 3-13 include the travel time through the Canadian port of entry, the bridge, the American port of entry, and the booth clearance time. Since only the booth clearance times were required for the VISSIM model, a Monte-Carlo simulation was used to determine the clearance time distribution for each border crossing. It was determined that a clearance time of 2-3 minutes for regular trucks would be realistic and a 1-minute clearance time for FAST trucks (see Figure 3-14 to Figure 3-16).

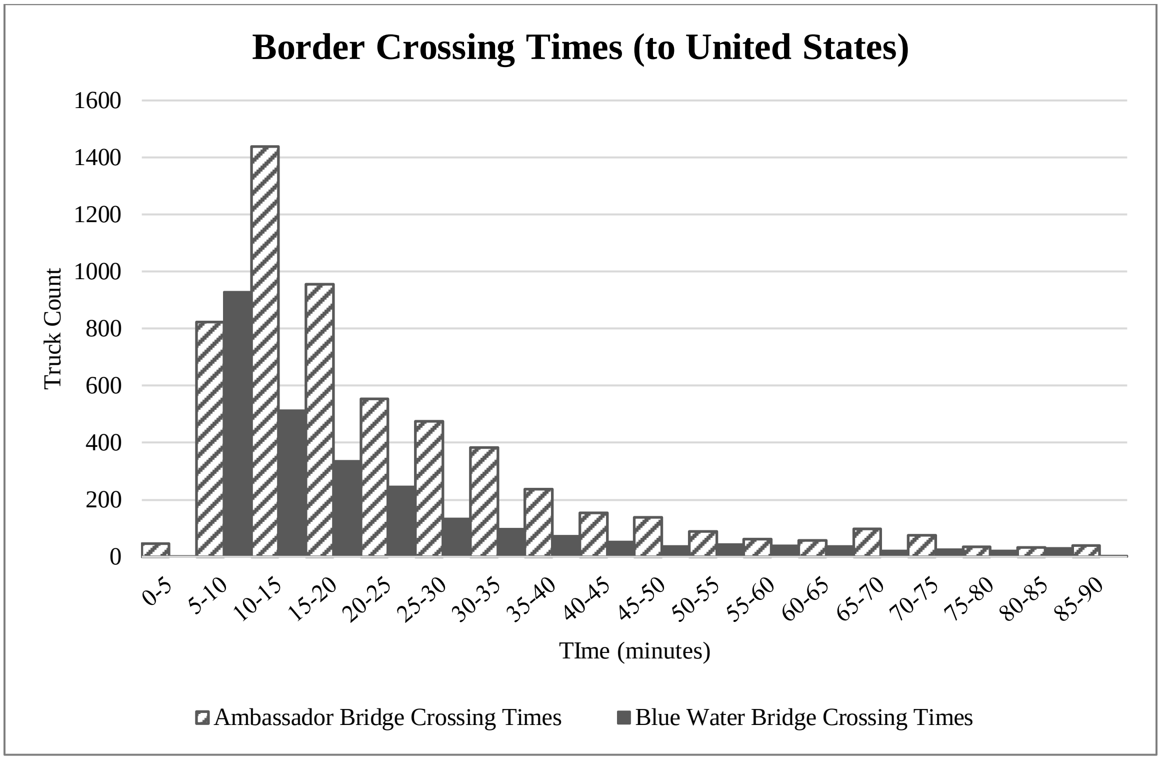


Figure 3-13 Border Crossing Time Distribution from GPS Data

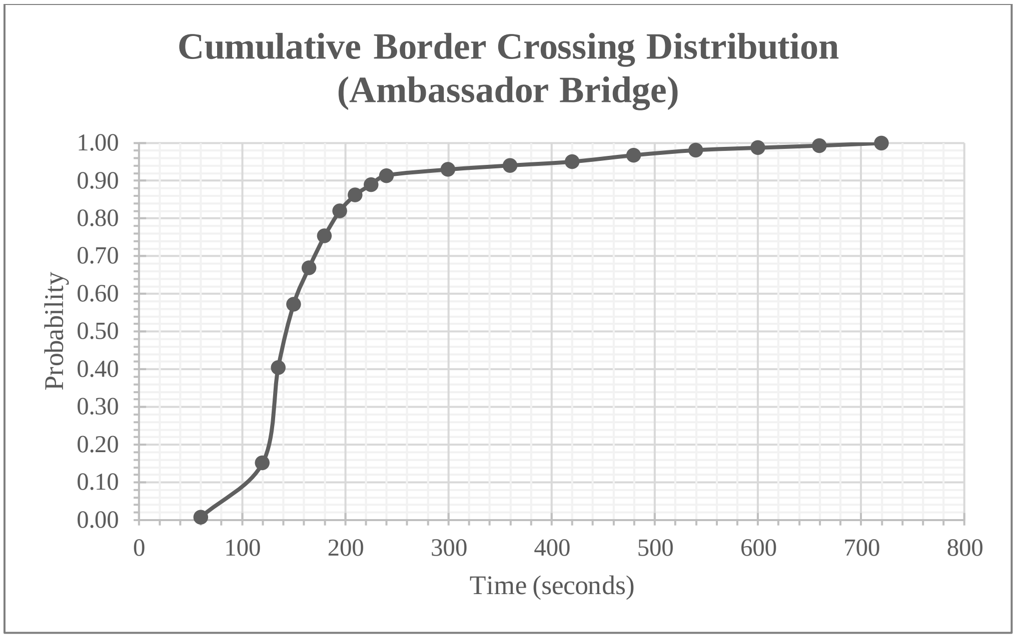


Figure 3-14 Border Crossing Distribution for Trucks at the Ambassador Bridge - Adapted from Gingerich et al. (2015)

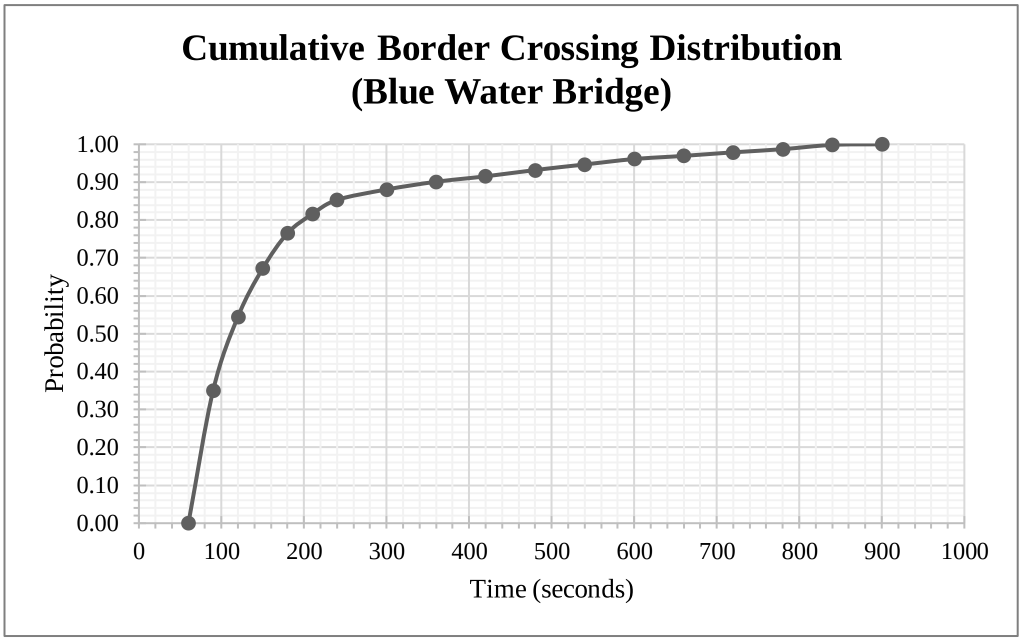


Figure 3-15 Border Crossing Distribution for Trucks at the Blue Water Bridge - Adapted from Gingerich et al. (2015)

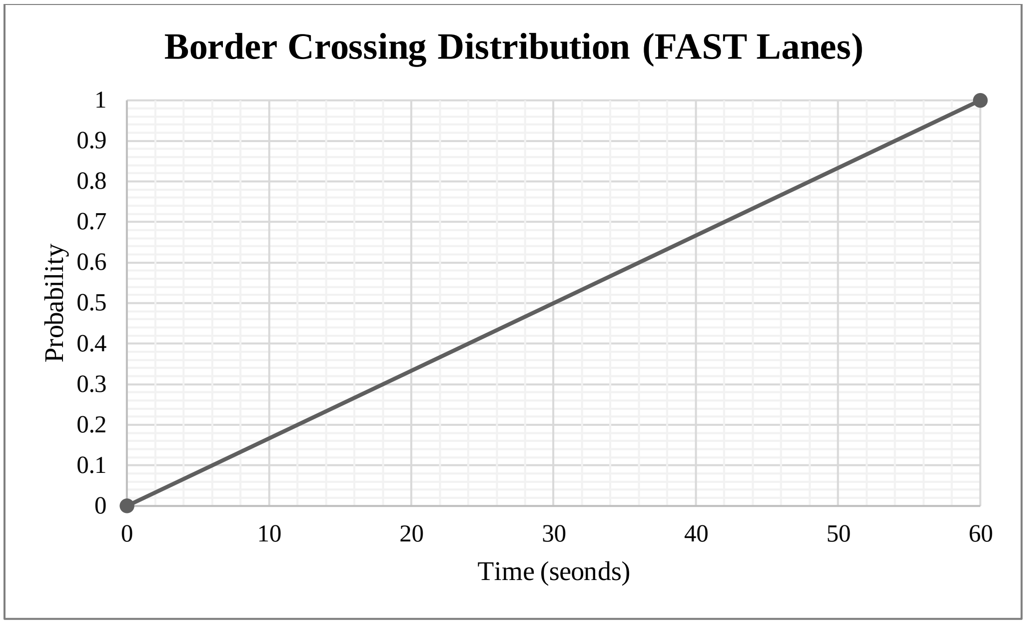


Figure 3-16 Border Crossing Distribution for FAST trucks

Traffic Analysis Phases

This section outlines the scenarios that were simulated in this thesis project. The DTA simulations were set to run for a maximum of 50 iterations with a convergence criterion of 95% of travel time of the previous run for 5 consecutive runs.

Phase 0 – No Delay (Connectivity Test)

The 'No Delay' phase was simulated to test the connectivity of the network ensuring that all links are connected and available for vehicles. This pre-analysis phase also established a base case simulation travel time and volume split on the network as it stands without any delays.

Phase 1 - Status Quo

The status quo scenario established a reference network that replicated existing traffic conditions such as border crossing splits between Ambassador Bridge and Blue Water Bridge (Gingerich, et al., 2015) and the travel time for OD pairs as reported by

Google Maps. Under the status quo, traffic originates from the Greater Toronto Area (GTA) and move on Highway 401 in southwestern Ontario towards the U.S. Here, traffic crossing to the U.S. has two border-crossings: The Ambassador Bridge in Windsor, Ontario and the Blue Water Bridge in Sarnia, Ontario. A few freight hubs were chosen in the U.S. as destinations. The passive GPS data available to us was used to develop these OD pairs. The border choice pattern and travel time was used as validation measures for the reference network. Once the network was validated by replicating existing conditions, the other scenarios were modeled in the VISSIM network. The FAST class trucks were also implemented in the model as 40% of all truck volume were assigned designated FAST lanes for faster clearance processing at the border (Maoh et al., 2016).

Phase 2 – Connected Vehicles in Traffic Stream

The objective of this scenario is to evaluate the cross-border traffic operations with the presence of connected vehicles in the traffic stream. An incident was modelled on Highway 401 for about 6 hours (8 am – 2 pm), a few kilometers after the decision point where trucks coming from the GTA split to move on Highway 402 towards the Blue Water Bridge in Sarnia or stay on Highway 401 towards the Ambassador Bridge in Windsor (See Figure 3-17). The presence of connected vehicles would test the communication of this incident to other connected vehicles and examine the border choice pattern. A sensitivity analysis at 20%, 40%, 60%, 80%, and 100% connected vehicles in the traffic stream was performed to assess the border choice patterns between the two border crossings. The incident is located at a distance of 200 meters from the decision point shown in Figure 3-17. Intuitively, the presence of an incident downstream on highway 401 will reduce capacity which may result in some delays on Highway 401. The rationale here is that if the information about the incident is relayed to connected vehicles upstream before the decision point, then some trucks may decide to switch route to Highway 402 to avoid potential delays on highway 401.

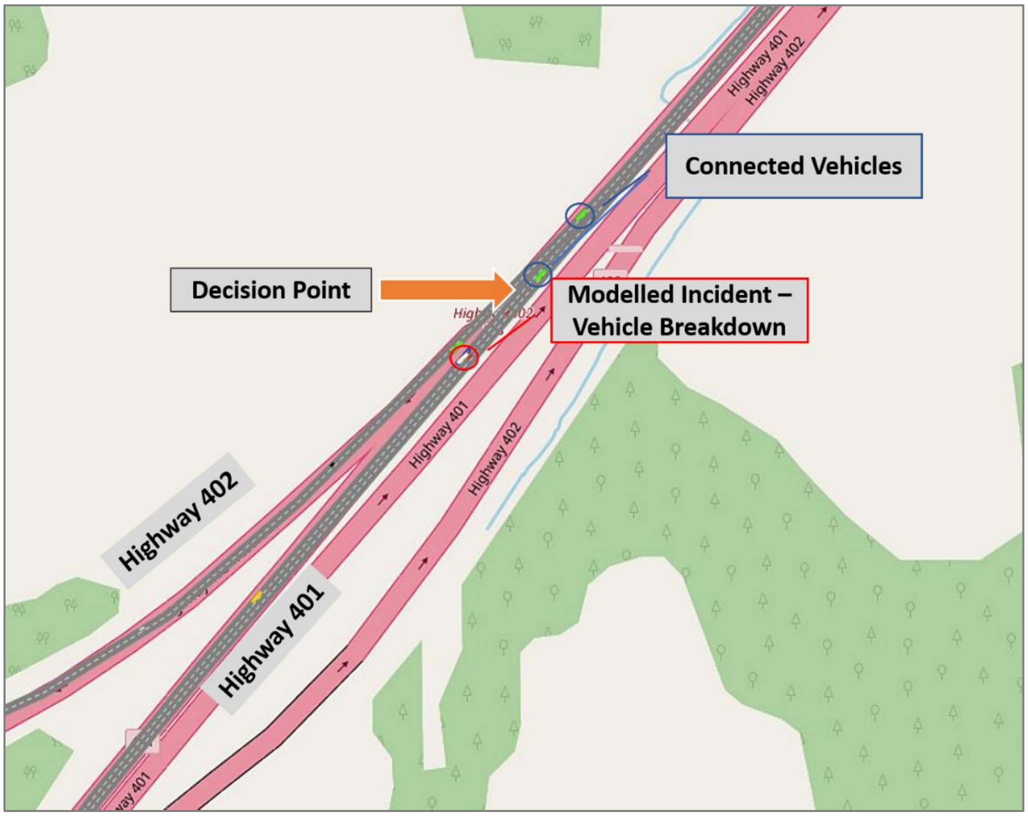


Figure 3-17 Vehicle Breakdown on Highway 401 - Modelled Incident

V2V Distance Distribution

The connected vehicle python program requires a distance distribution to define the range of V2V communication. As a standard, 300 m was used for short range communication between vehicles. The distribution used for the V2V scenario is presented in Figure 3-18.

VISSIM implements a Monte Carlo simulation on all distributions in the software where it calculates the probability of an event depending on the cumulative distribution curve (e.g., Figure 3-18). The probability of all connected vehicles receiving the message increases with the chosen distribution.

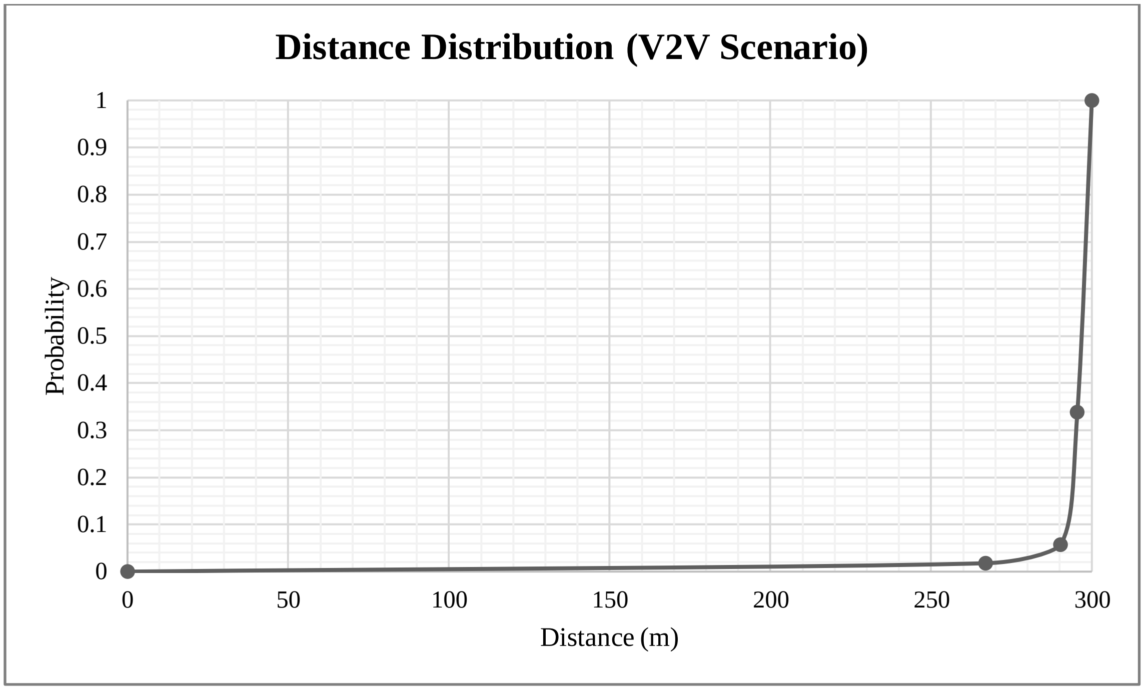


Figure 3-18 Distance Distribution for V2V Scenario

Phase 3 – Effects of Connected Vehicles in a Network with Border Delay

Land border crossings experience delays for various reasons which can cause extensive backups and delays. These delays can cause prolonged congestion and economic loss. For instance, the Ambassador Bridge experience delays on the U.S. side from time to time. According to Chen (2019) "*Delays on the U.S. side of the Ambassador Bridge have resulted in constant traffic congestion in the northbound lanes of Huron Church Road — particularly in terms of transport trucks*". If the backup occurring at one border crossing (e.g., Ambassador Bridge) is communicated to connected vehicles before the decision point shown in Figure 3-17, then it is possible that some trucks may choose to change route (e.g., switch to Highway 402 to cross via the Blue Water Bridge) to reach their destination to save time and avoid the backup.

The objective of this phase of the analysis is to test the effect of an extensive border delay at one of the crossings and evaluate the resulting traffic pattern for both crossings. The Ambassador Bridge will be the crossing experiencing an 8-hour delay where traffic is stalled. The first scenario will be simulated without the presence of connected vehicle to establish a reference benchmark. The connected vehicles will be modeled in a separate scenario to evaluate the impacts of V2I for long distance communication. The simulated delay is presented in Figure 3-19.

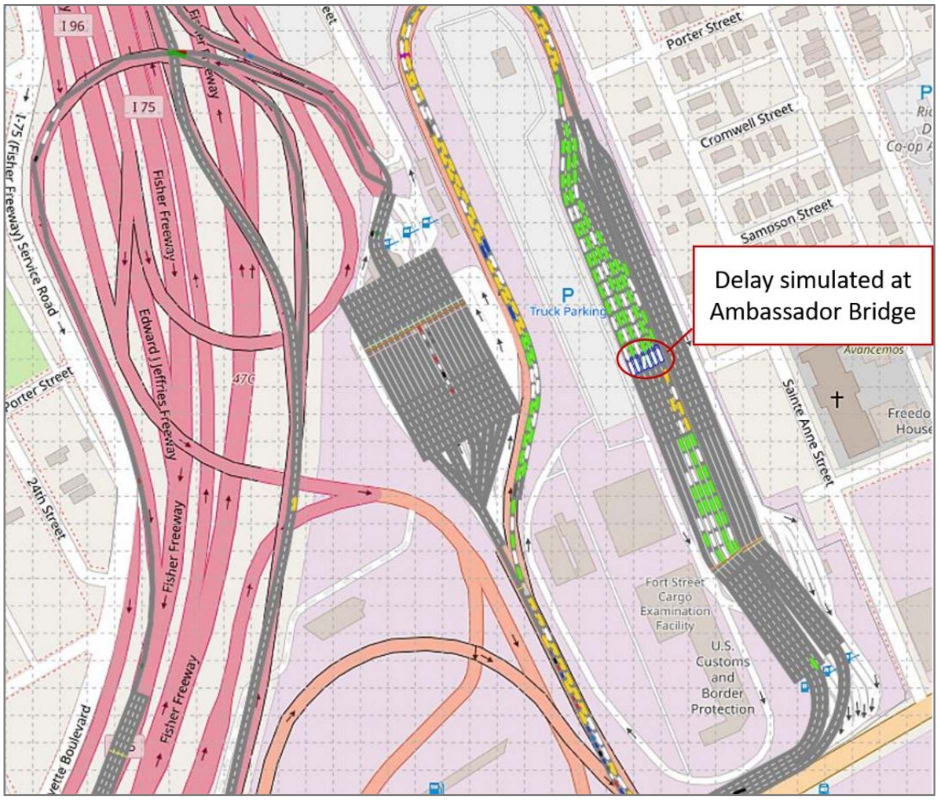


Figure 3-19 Simulation of Delay at the Ambassador Bridge - Border Delay Scenario

V2I Distance Distribution

To simulate Vehicle-to-Infrastructure (V2I) scenarios, the receiving infrastructure was set to be before the decision point for the two border crossings. The distance distribution curve was the same to ensure that the choice was deterministic. That is, the curve was intentionally chosen to ensure that all vehicles driving on Highway 401 before the decision point to continue on Highway 401 (to Windsor) or switching to Highway 401 (to Sarnia) will receive information about the ongoing delay at the Ambassador Bridge. Thus, the V2I scenarios could be implemented in the microsimulation. The distance cumulative distribution is presented in Figure 3-20.

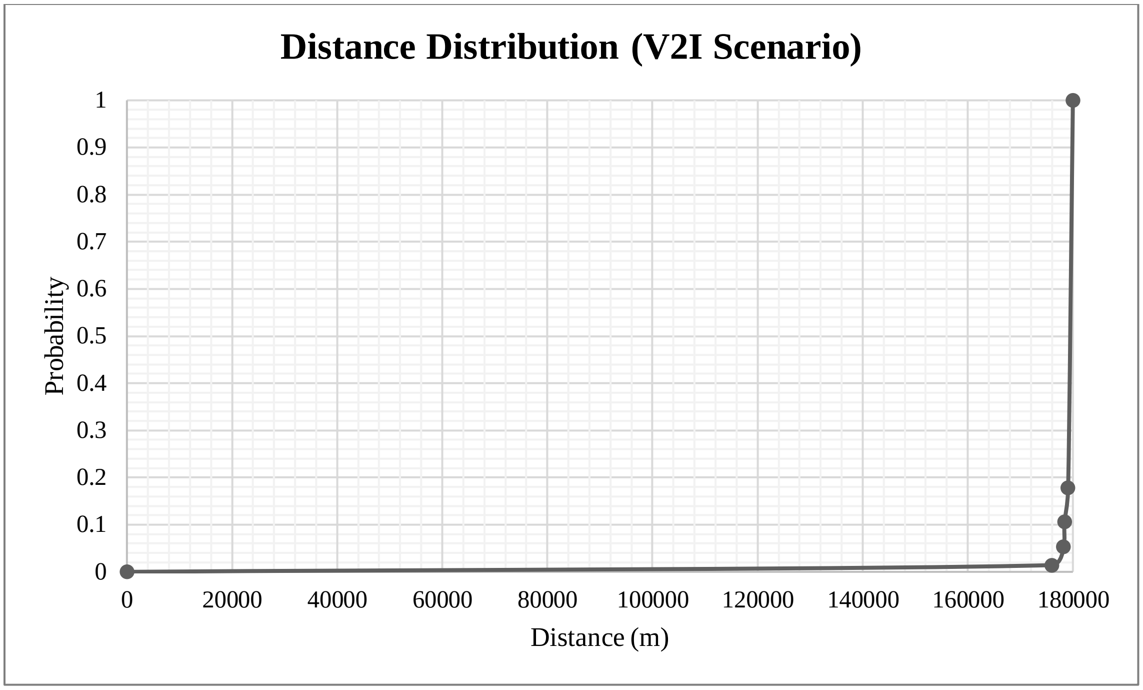


Figure 3-20 Distance Distribution for V2I Scenario

4. RESULTS AND DISCUSSION

To evaluate the overall performance of the border traffic microsimulation model presented in the previous chapter, two measures of performance were used:

- Travel time between O-D pairs
- Truck volume split between the two border crossings

The comparison of travel times between Google Maps and each of the scenarios serves as a validation measure of the border crossing distributions, Figure 3-14 and Figure 3-15, signal timing plans, as well as speed distributions assigned in the model. If the travel time is comparable to Google Maps, an established mapping service, then the network is performing well with the parameters set for it in the model.

The volume split between the two available border crossing serves a similar purpose as it validates the route choice behavior of reference datasets and presents the applicability of the DTA to a border choice scenario. Furthermore, it allows for examining the effects of disruptive technology and extensive delays on border choice pattern and in turn the travel times between the O-D pairs.

It should be noted that the network created mainly consisted of the major highways usually utilized by commercial trucks between the analyzed OD pairs and excluded local roads as the modelling of local traffic was not within the scope of the project, except for the Windsor-Essex region, where local traffic interacts with border traffic on the corridor leading to the border. Therefore, it was important to introduce Windsor's local traffic as background traffic on the analyzed corridor.

Travel Time Results – Phase 0 and Phase 1

The following figures present the travel time results for the No Delay (Phase 0) and Status Quo (Phase I) Scenarios. The objective of comparing these two scenarios is to ensure that there is complete network connectivity as well as establish a benchmark reference network to test the other planned traffic phases. Figure 4-1 to Figure 4-5 present the travel time between the starting point of traffic (i.e., near Woodstock, Ontario) and key U.S. destinations. Each figure depicts the extracted travel time from Google Maps versus the outputs of the microsimulations for Phases 0 and 1. There's an overall trend that emerges indicating that the travel time for phase 0 is generally lower than travel time reported by Google Maps. The network in Phase 0 reports times from the origin to the destinations with the assumption of zero border delays. This phase was modeled to ensure network connectivity between the OD pairs and as such the travel times from this run are expected to be lower than what would normally be reported by Google Maps. Simulated travel times from Phase 1 are higher than Phase 0 and Google Maps. The travel time reported by Google Maps pertains to mainly passenger vehicles, which is typically lower than the time experienced by commercial trucks. The path travelled by trucks at the border facility may also be different resulting in longer travel times than passenger vehicles. Since most commercial vehicles are subjected to inspection at the borders, it is expected that the travel times for trucks would be higher than what is reported in Google Maps. Figure 4-2 presents an interesting scenario for Toledo, OH. The trucks traveling to Toledo only choose Ambassador Bridge to cross into the U.S even though the border crossing time through Blue Water Bridge is not much different. The time from Google Maps was reported for both bridges for consistency purposes. We believe none of the trucks heading to Toledo end up choosing the Blue Water Bridge because the Ambassador Bridge provides the shortest path. That is, the travel time plus the delays at the Ambassador Bridge is less than the travel time plus the delays at the Blue Water Bridge. Given that Toledo is south of Michigan, it is intuitive to assume that trucks heading there will favor the Ambassador Bridge. Since Phase 1 travel times were comparable to Google Maps, the network was deemed functional and was then used for further analysis where disruptive technology was introduced in the border crossing traffic stream.

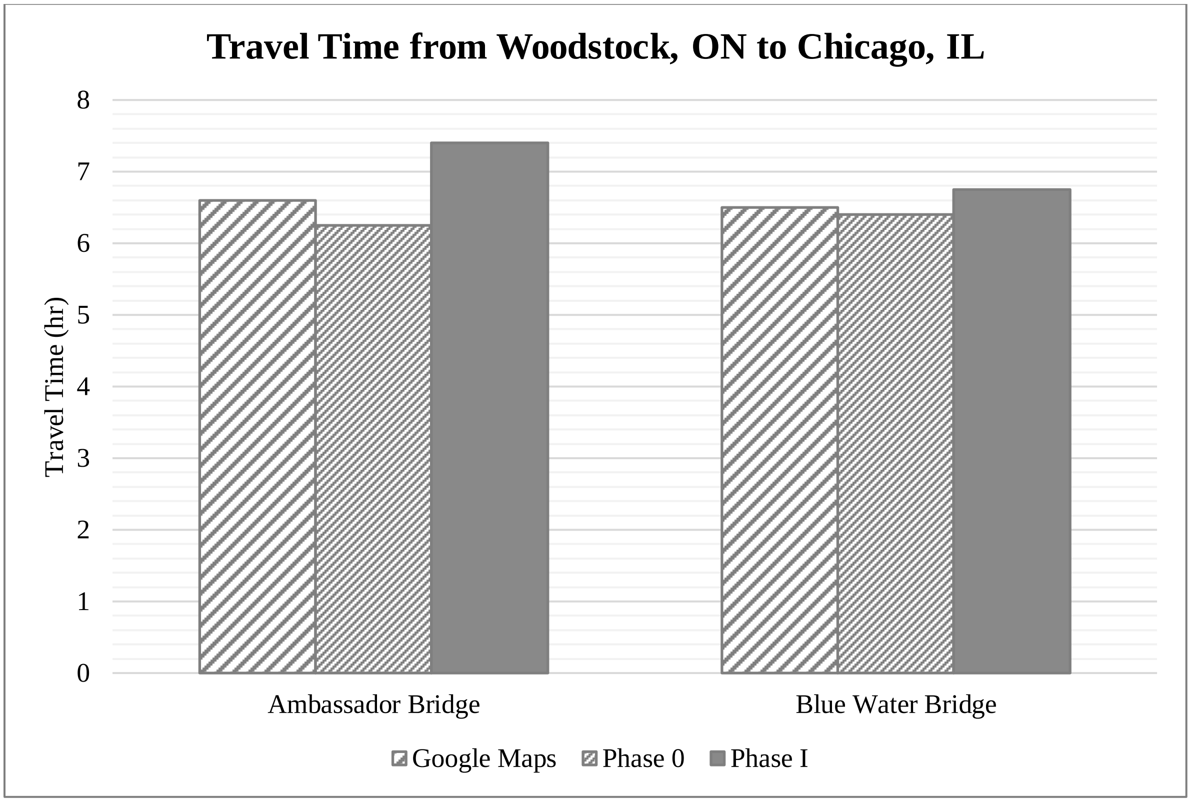


Figure 4-1 Travel Time Results for Phase 0 and Phase 1 from Woodstock, ON to Chicago, IL

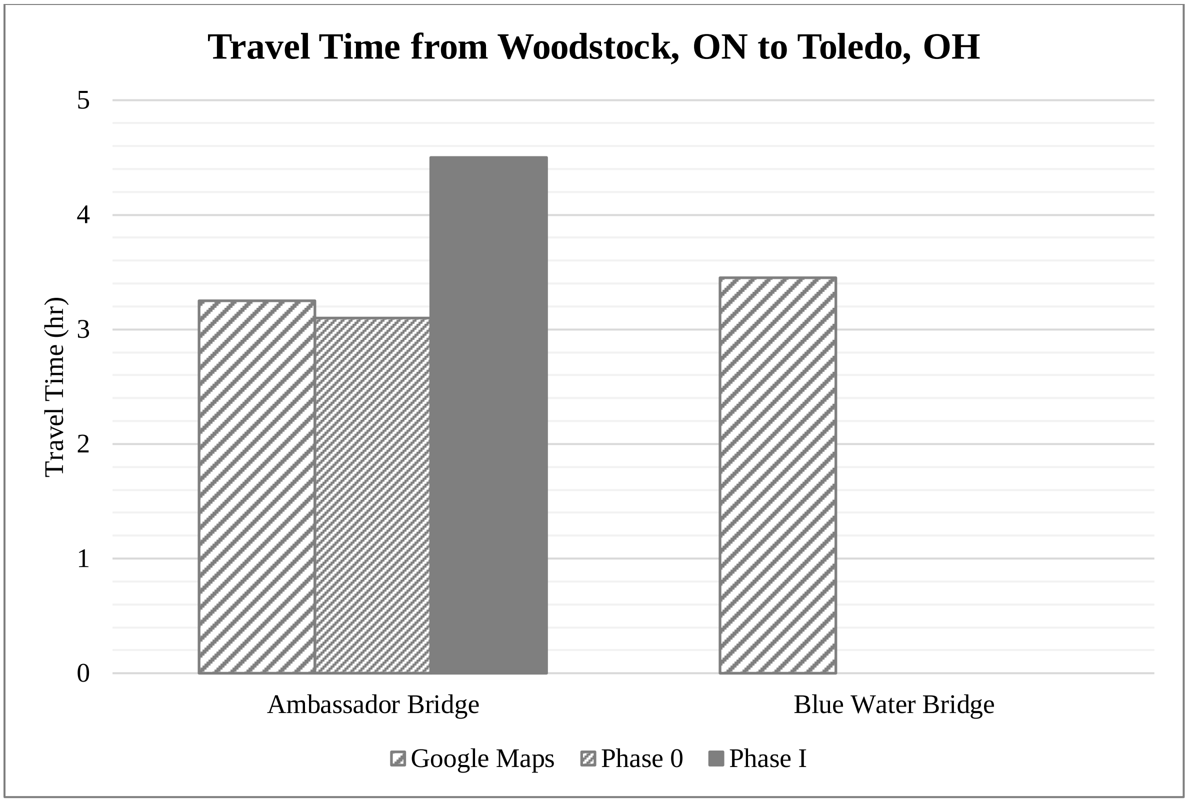


Figure 4-2 Travel Time Results for Phase 0 and Phase 1 from Woodstock, ON to Toledo, OH

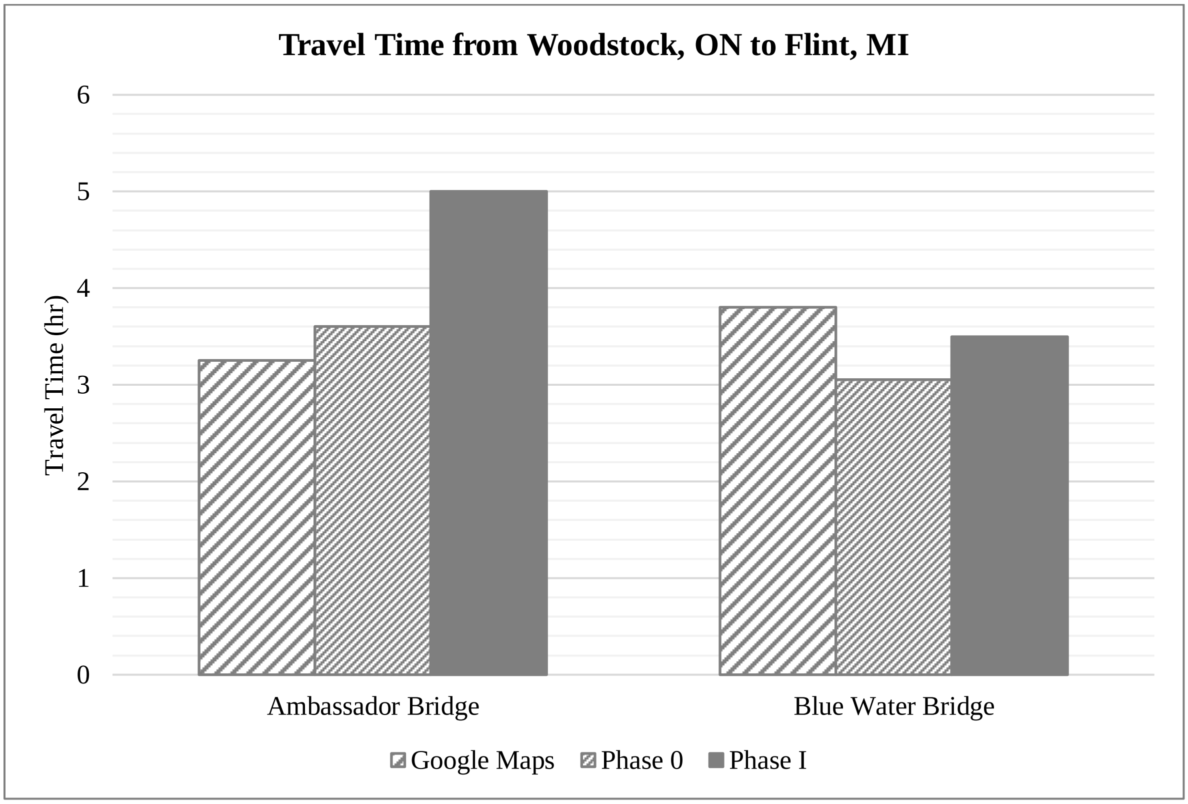


Figure 4-3 Travel Time Results for Phase 0 and Phase 1 from Woodstock, ON to Flint, MI

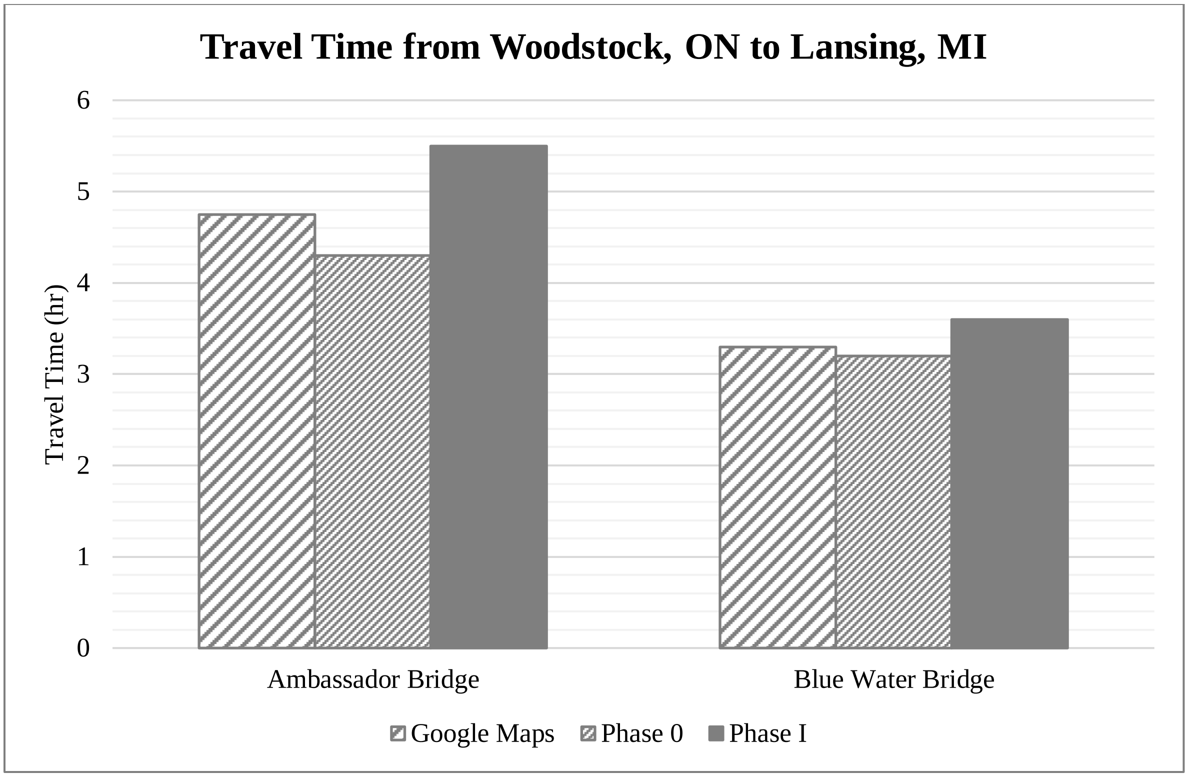


Figure 4-4 Travel Time Results for Phase 0 and Phase 1 from Woodstock, ON to Lansing, MI

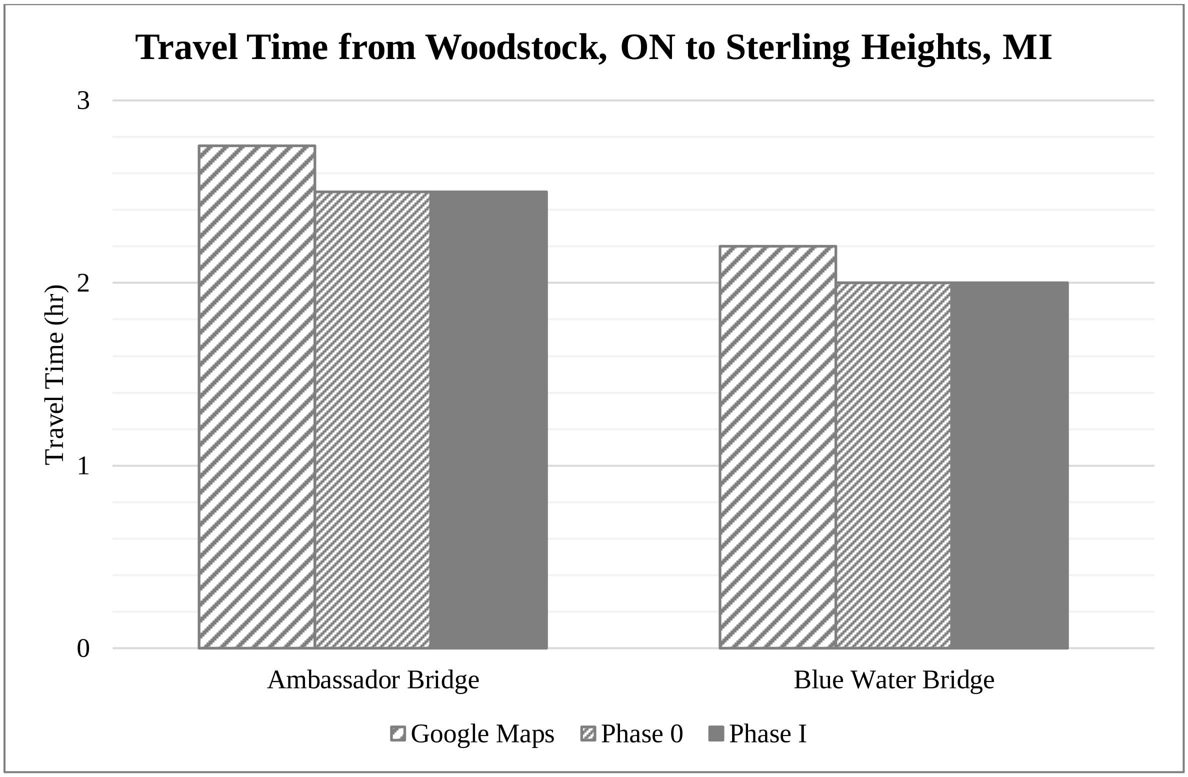


Figure 4-5 Travel Time Results for Phase 0 and Phase 1 from Woodstock, ON to Sterling Heights, MI

Border Choice Pattern – Phase 0 and Phase 1

This section presents the border choice pattern extracted from Phases 0 and 1 as presented in Figure 4-6 and Figure 4-7. The Ambassador bridge processes approximately 60% of the traffic in both scenarios. The results suggest that the DTA of VISSIM is able to mimic the border choice behavior and associated patterns observed in the field based on the utilized reference datasets.

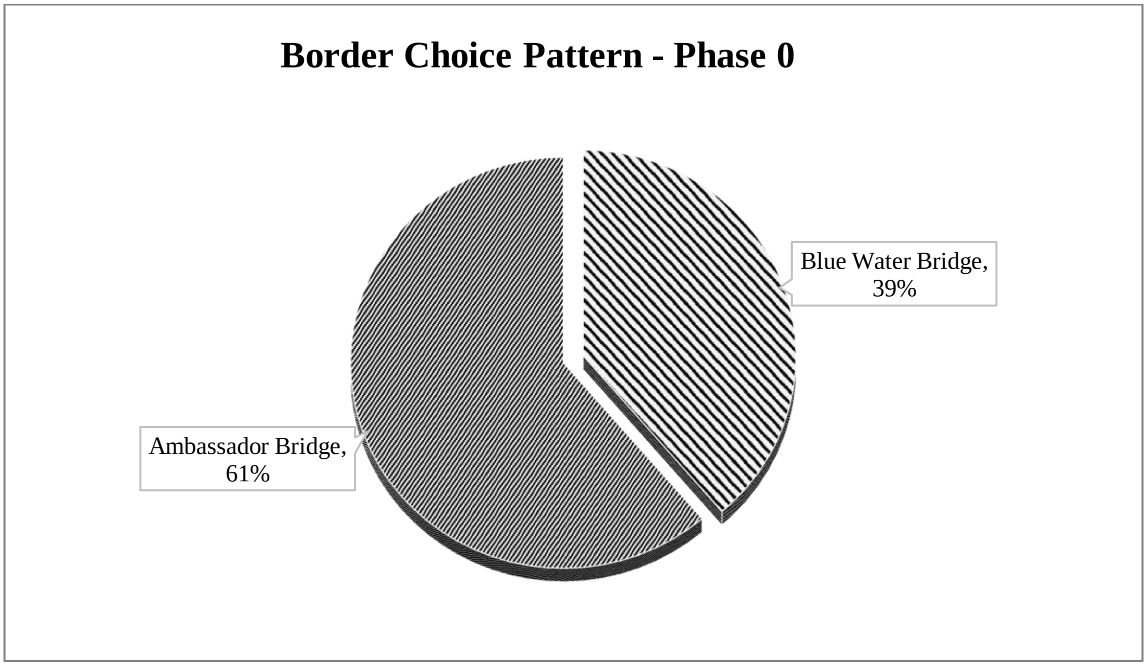


Figure 4-6 Border Choice Pattern for Traffic Analysis Phase 0

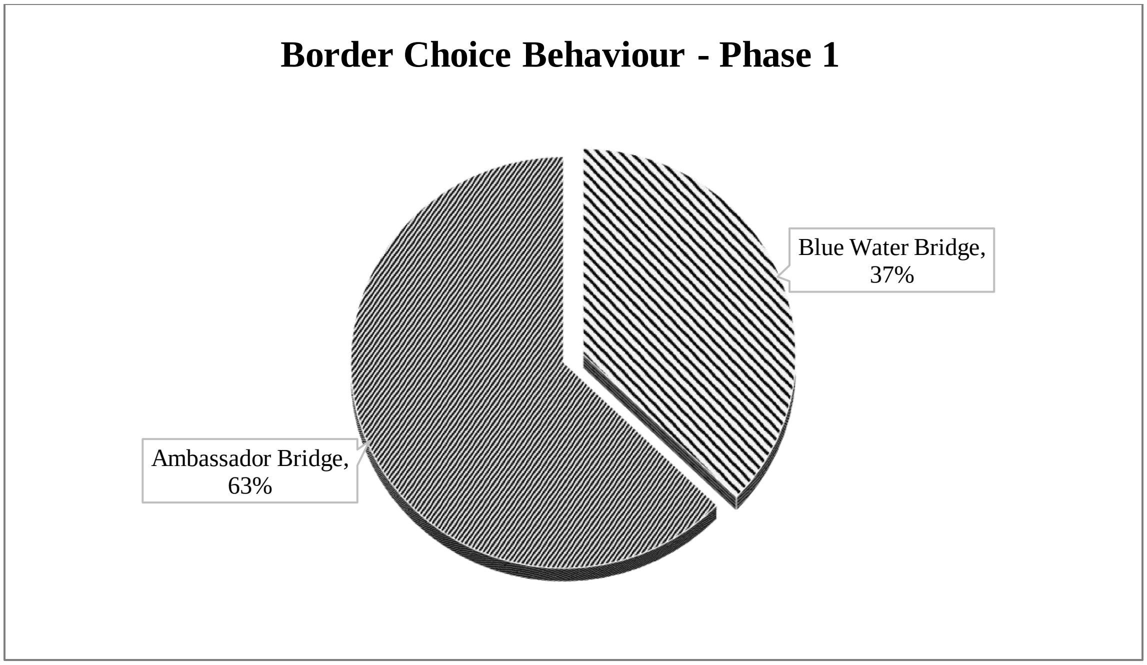


Figure 4-7 Border Choice Pattern for Traffic Analysis Phase 1

Connected Vehicle Demo Network Results

As noted in Chapter 3, a simplified demo network was constructed and tested to examine the connected vehicles python script needed to simulate the real Ontario-U.S. network. As Figure 4-8 shows, the network consisted of three paths, two of which (Path 1 and Path 2) were equal in length and capacity. Path 3 is introduced with half of the capacity of Path 2. The network was first tested without an accident or the presence of V2V to establish a benchmark reference. An accident was then simulated on Path 2 past a decision point in which traffic moving on path 2 can choose to either continue on path 2 or switch to path 3 in case conditions near the accident become highly congested due to the accident. A total of 1500 vehicles are assumed to move between the origin and destination. The duration of the simulation was 1 hour, and the incident was simulated for approximately 30 mins. There were three classes of vehicles defined: HGV (Regular Trucks), HGV with

C2X (no message) and HGV with C2X (active message). The simulated network is presented in Figure D-1 and Figure D-2, in APPENDIX D:.

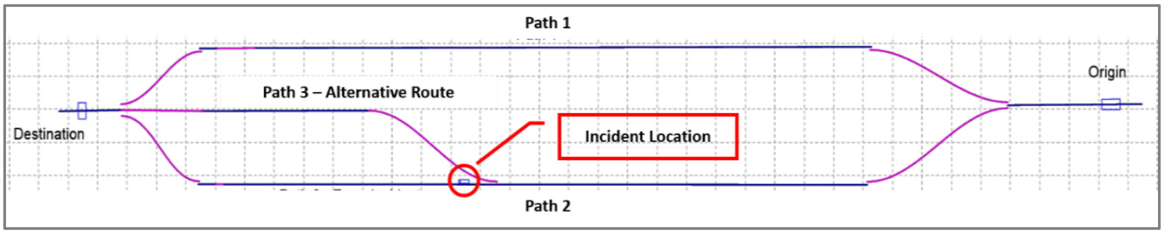


Figure 4-8 Demo Network

Table 4-1 presents the results from three scenarios: a base case, one with an accident on Path 2 but without the presence of connected vehicles and one with an accident and with connected vehicles in the traffic stream. Under the first scenario, the 1500 vehicles start emerging on Paths 1 and 2. Ideally, if the network connecting the origin and destination consisted of only Paths 1 and 2 (i.e. no alternative Path 3), then the traffic on each link would be roughly 50% of the total 1500 flow (i.e. 750 vehicles on each path). However, due to alternative Path 3, the split between Paths 1 and 2 is in favor of Path 2. According to the simulated results, 481 (32%) vehicles use Path 1 while 1019 (68%) of the vehicles travel towards Path 2. The traffic is further split between Paths 2 and 3 with 521 (34%) and 498 (33%) vehicles, respectively. In the absence of an accident and without the presence of V2V in the traffic stream, the flow is split almost evenly between the 3 paths.

In the second scenario, the DTA split the 1500 vehicles such that 514 (34%) use Path 1 while 986 (66%) use Path 2. These 986 vehicles then branch to move onto the remainder of Path 2 and alternative Path 3 towards the destination. As the incident is continuously simulated on Path 2, vehicles moving towards the destination will find it advantageous to shift to paths with either higher capacity or shorter travel times. Due to the accident, the split of the 986 vehicles between Paths 2 and 3 are 45% and 55%, respectively.

The results pertaining to the V2V scenario indicate that the communication between connected vehicles is effective. Since the vehicles receive the incident information at the origin, it is intuitive that Path 1 experiences a slight increase in traffic volume. Out of the 1500 vehicles, 530 vehicles (35%) choose Path 1 and 970 vehicles (65%) choose Path 2. Due to the incident on Path 2, traffic further splits between Paths 2 and 3 with 44% and 56% of traffic, respectively.

Table 4-1 Demo Network Results

	Base Case (No accident, No V2V)		**Without V2V in Traffic Stream**		**With V2V in Traffic Stream**	
Path #	**Travel Time**	Path Volume	**Travel Time**	**Path Volume**	**Travel Time**	**Path Volume**
1	00:54.6	481	00:55.6	514	00:54.0	530
2	00:52.9	521	00:55.6	471	00:57.2	429
3 (Alternative)	00:53.5	498	00:55:2	515	00:54.8	541

The results presented for scenario 3 in

Table 4-1 were extracted from a scenario with a 60% penetration rate of connected vehicles in the traffic stream. Since the objective of the demo network was to test the functionality and applicability of the Python code in to the DTA as well as the network, a sensitivity analysis with other penetration rates was deemed not necessary. Connected vehicles in the traffic stream are able to communicate with traffic upstream about any unusual events that may disrupt the traffic flow. As the incident is simulated in the network, vehicles are able to communicate this information with upstream traffic. The communication happens simultaneously with the assignment making the difference in traffic volume between simulations much smaller than the first scenario. Since most vehicles try to avoid the incident and choose other routes, the changes between simulation runs are not drastic. The change can still be seen, however small, that a higher number of vehicles choose Paths 1 and 3 rather than Path 2, the path where the incident occurs. It also bears noting that path 3 is able to sustain more traffic volume with half the capacity and shorter travel time, than Path 2, for vehicles to avoid the incident and travel to the destination zone. In summary, due to the presence of connected vehicles, a total of 42 vehicles reacted by altering their routes from Path 2 to Paths 1 and 3.

The demo network was developed to test the functionality of the Python code that was required to simulate connected vehicles in the network. The results extracted show that the integrated code was able to simulate connected vehicles effectively and it could now be used in the cross-border regional network to model scenarios with disruptive technology and analyze cross-border movement as well as test the capability of the dynamic traffic assignment.

Traffic Analysis Phase II – Connected Vehicles in Traffic Stream Results

The following section presents the simulation results extracted from the sensitivity analysis performed for the connected vehicles scenario.

Border Choice Pattern

The sensitivity analysis was performed to determine how the presence, as well as the concentration of connected vehicles in the traffic stream would affect the border choice pattern observed in the base case scenario. The travel times were also extracted to examine the effects of connected vehicles, if any, on the overall travel times between O-D pairs. The sensitivity analysis results, as shown in Figure 4-9, indicate a trend where traffic starts switching to the Blue Water Bridge. As the penetration rate of connected vehicles increases in the traffic stream, a higher number of trucks choose Blue Water Bridge to travel to the U.S. The pattern also indicates that there is communication between vehicles about the incident and as the penetration increases, a higher number of vehicles receive the incident information. As noted earlier in the chapter, approximately 50% of the simulated trucks travel to Toledo, OH. The travel time analysis indicates that the DTA always assigns this traffic through the Ambassador Bridge route resulting in a border choice pattern that favors this crossing.

The base case for this phase simulated an incident on Highway 401 without the presence of connected vehicles in the traffic stream. The border choice behavior, presented in Figure 4-9, indicates that the Ambassador Bridge processes 67% of the truck traffic in this scenario. Since the incident is simulated on Highway 401, it would be expected that a higher percentage of trucks would travel through Blue Water Bridge due to reduced capacity on the path leading to the Ambassador Bridge. The incident is simulated for about 6 hours (8 am – 2 pm) during which the traffic switches to Blue Water Bridge increasing the delay at this crossing, as presented in Figure 4-10. According to the figure, delays start building at 8 am and continue to do so over the 6 hours of the simulated incident. However, such delays continue to spill over for several hours after the incident clears. The increased levels of delays at the Blue Water Bridge will entice trucks to favor the Ambassador Bridge since this crossing will not experience significant delays, resulting in 67% truck share for this crossing. For realistic V2V simulation purposes, the incident needs to be in 300 meters of a location that allows vehicles to make a decision to change their route to Highway 402 to avoid the incident, if they so wish. A large percentage of the simulated trucks, approximately 50% as extracted from the GPS dataset, travel to Toledo for which Ambassador Bridge is always the chosen options, regardless of delays on the route. The total distance between Woodstock and Toledo is 314 km through the Ambassador Bridge route and 346 km through the Blue Water Bridge route. Since the DTA algorithm looks for the shortest path between the O-D pairs, the Toledo traffic was always routed through Ambassador Bridge, even with a delay of 6 hours.

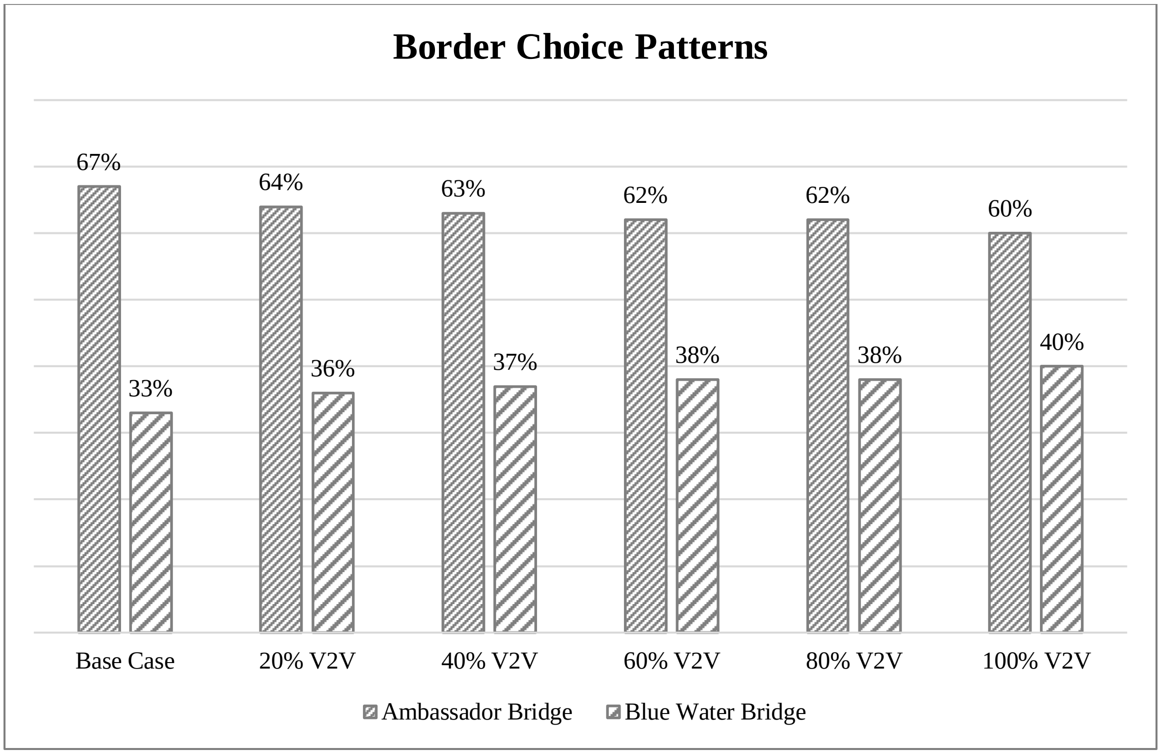


Figure 4-9 Border Choice Patterns - Traffic Analysis Phase II

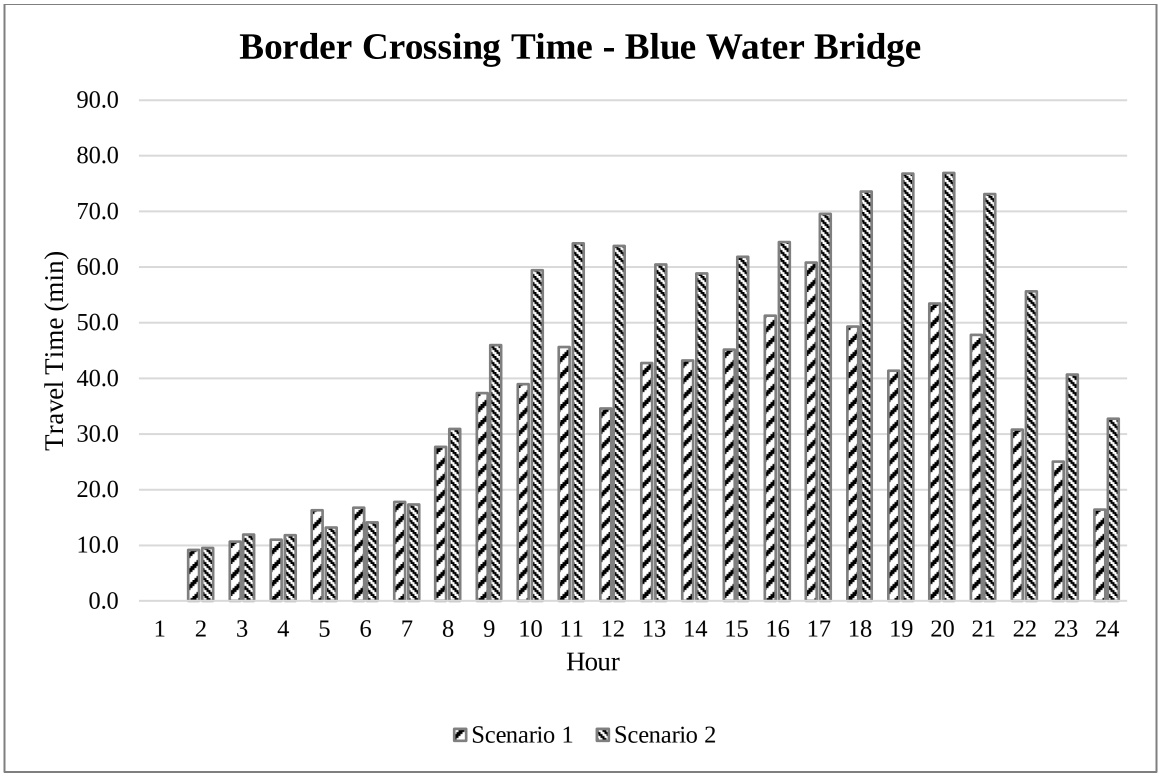


Figure 4-10 Border Crossing Travel Time - Blue Water Bridge

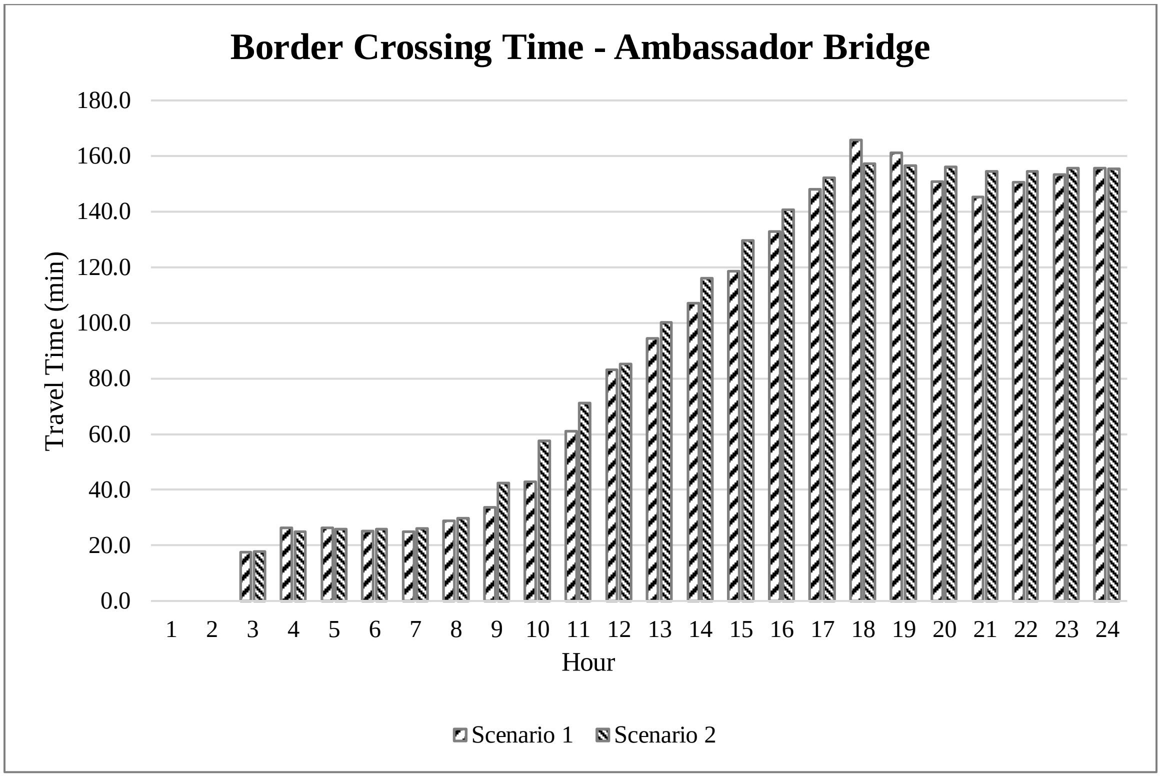


Figure 4-11 Border Crossing Travel Time - Ambassador Bridge

Travel Time

The travel time results are presented to supplement the border choice results from the sensitivity analysis. The data explains if a border crossing was chosen and the average travel times experienced by vehicles on the crossings. Google Maps is used as a benchmark to assess how well the border crossing is performing in the model. If the travel time is lower than the times reported by Google Maps, then the model needs to be recalibrated to ensure that travel times are comparable, if not higher.

For the purpose of this analysis, the base case travel time should be used as it provides a better reference for the sensitivity analysis. The travel time results for both border crossings at each penetration rate are presented in Figure 4-12 to Figure 4-16. It should be noted that as the percentage of connected trucks increases in the network, the other classes of trucks are proportionally adjusted. There are dedicated FAST lanes in the network that only process FAST class trucks. The increase in connected trucks results in a higher volume at the regular processing lanes, adding to the travel times as the penetration rate increases. An overall increase in travel time is observed at both crossings. The traffic processed at the border crossings decreases due to the FAST lanes no longer being available to trucks. The truck volumes processed at both bridges are presented in Table 4-2. It can be noted that as the penetration rate increases, the number of trucks processed at the crossings decreases resulting in larger delays at the borders which are presented in the next section of this chapter.

Table 4-2 Processed Truck Volume Results

	Ambassador Bridge		Blue Water Bridge	
Scenario	**Vehicles**	**%**	**Vehicles**	**%**
Base Case	4413	67	2152	33
20% V2V	3883	64	2163	36
40% V2V	3500	63	2029	37
60% V2V	3108	62	1872	38
80% V2V	2865	62	1786	38
100% V2V	2578	60	1751	40

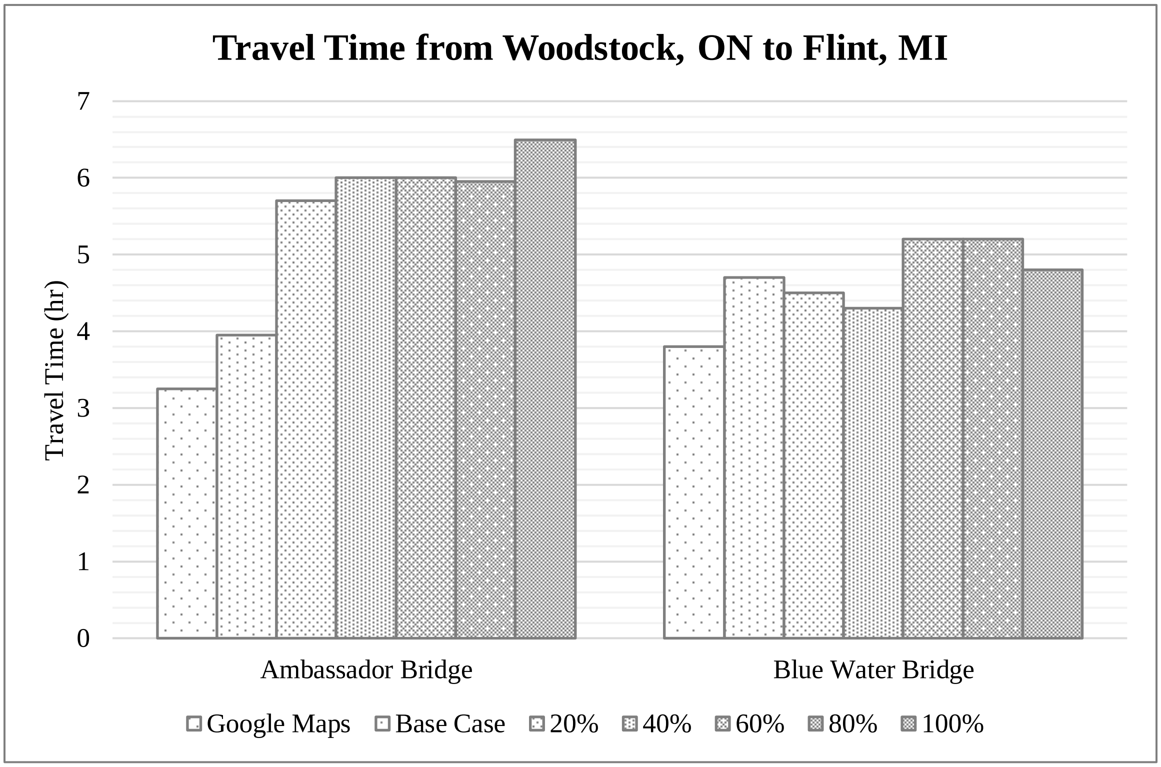


Figure 4-12 Travel Time Comparison – Woodstock, ON to Flint, MI

Figure 4-12 presents the results for Flint, MI. The base case results in a travel time of approximately 4 hours at both crossings. The travel time steadily increases at the

Ambassador Bridge which is expected but fluctuates at the Blue Water Bridge. The fluctuations could be a result of stochasticity for each simulation. Some simulations process more vehicles than others and the average may vary slightly for each scenario. However, the overall trend still indicates an increase in travel time for Blue Water Bridge as well.

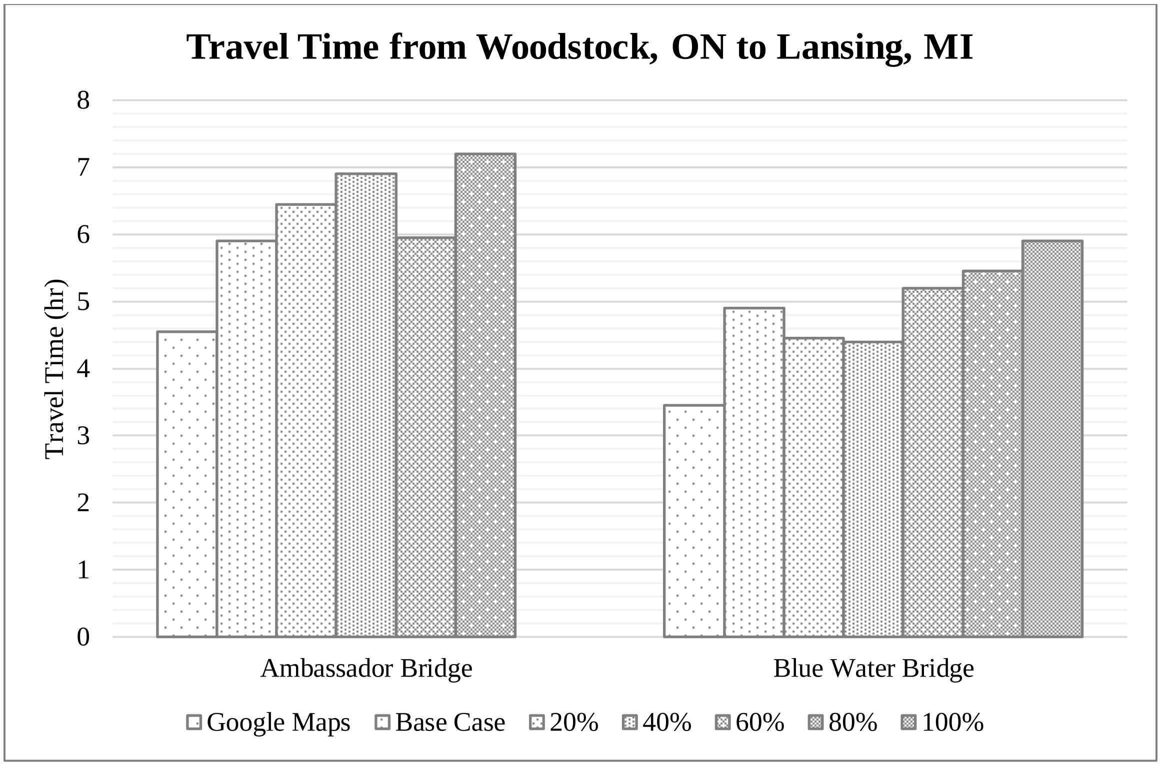


Figure 4-13 Travel Time Comparison – Woodstock, ON Lansing, MI

The travel times from Woodstock to Lansing, MI are presented in Figure 4-13. The increasing trend is more pronounced for both crossings for this destination. An interesting result in this scenario is that with 100% V2V in the traffic stream, all trucks travelling to Lansing choose the Blue Water Bridge.

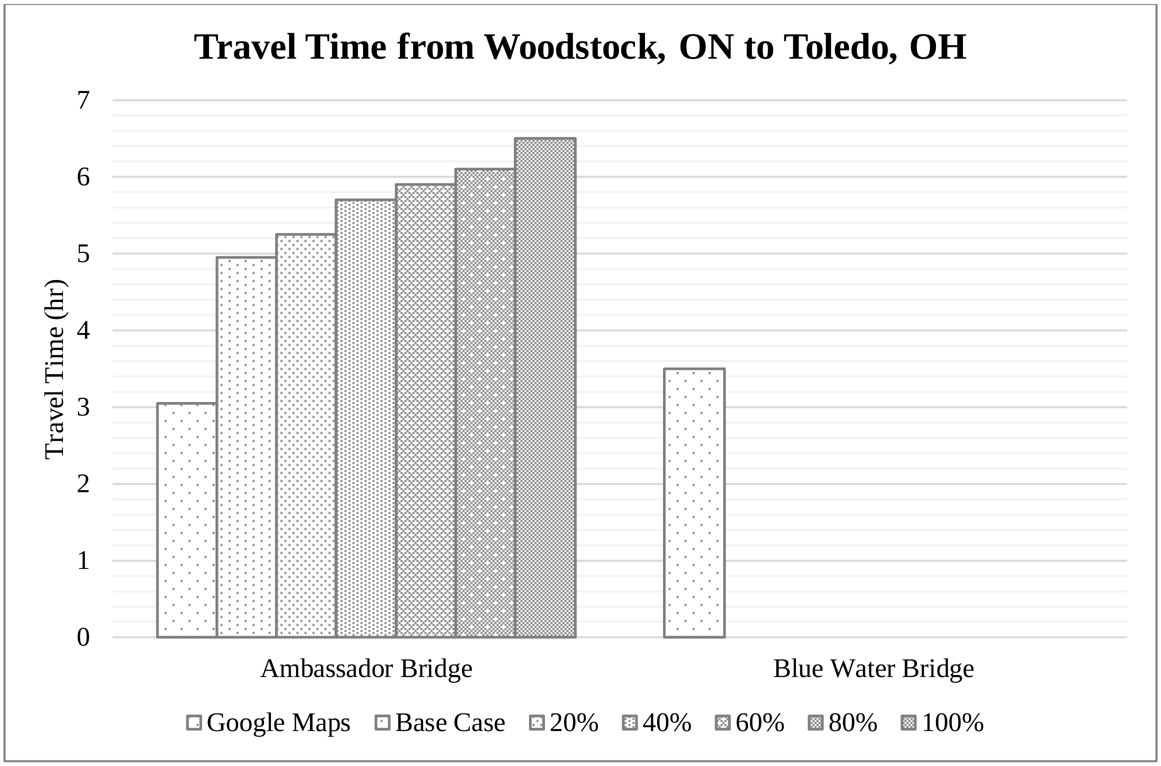


Figure 4-14 Travel Time Comparison – Woodstock, ON to Toledo, OH

The travel times from Woodstock to Toledo are presented in Figure 4-14. As noted in the previous phases, all trucks travelling to Toledo choose Ambassador Bridge to cross the border. The overall travel time increases as the penetration rate increases due to the FAST lanes not being available for processing some of the traffic.

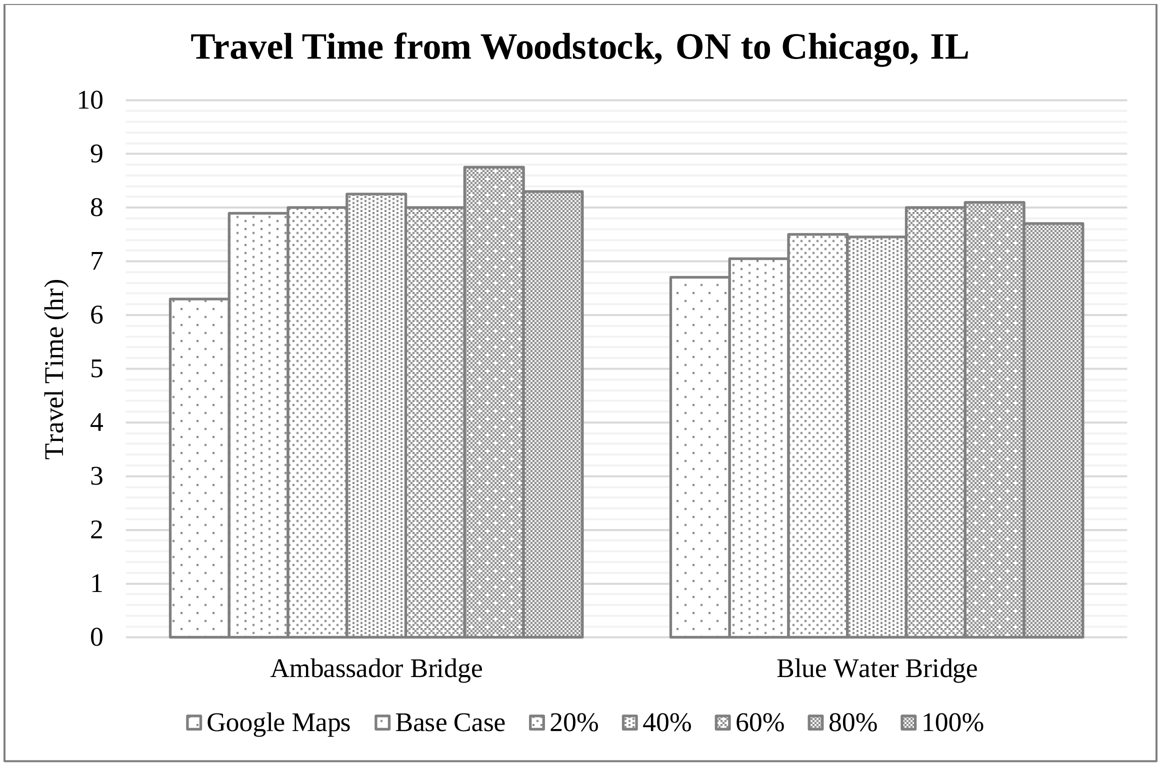


Figure 4-15 Travel Time Comparison - Woodstock, ON to Chicago, IL

The travel time to Chicago is presented in Figure 4-15. There is an overall increase in travel time from the base case to the 100% V2V scenario. The travel times for both crossings to Chicago are relatively similar as also observed in Google Maps, between 6.5 to 7 hours, depending on the time of travel.

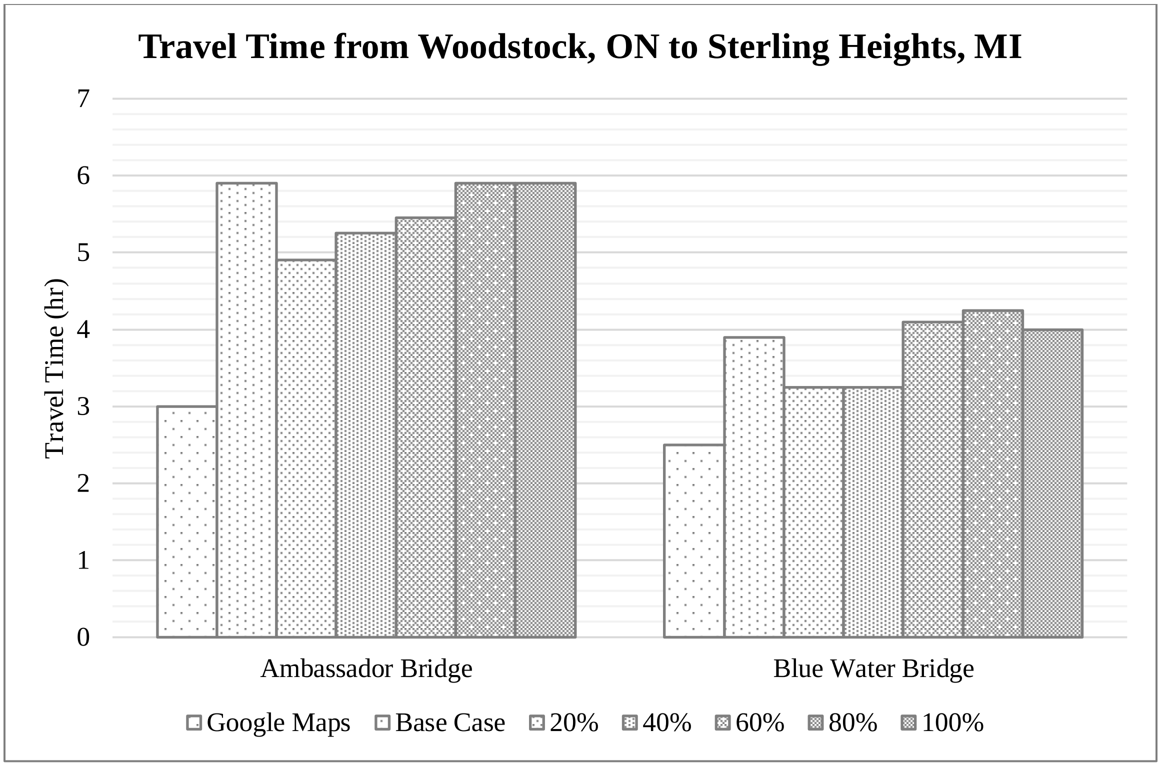


Figure 4-16 Travel Time Comparison - Woodstock, ON to Sterling Heights, MI

The travel times for Sterling Heights, MI are presented in Figure 4-16. As noted in the earlier figures, this destination also follows the same trend of an overall increase in travel time as the penetration rate increases. The stochasticity of the iterations can result in fluctuations between the scenarios.

Traffic Analysis Phase III – Effects of Connected Vehicles in a Network with Border Delay Results

The V2I scenario was modelled with an 8-hour delay (7 am – 3 pm) at the Ambassador Bridge with a 60% connected vehicle penetration rate. The results are presented in this section.

Base Case – Border Delay with No V2I

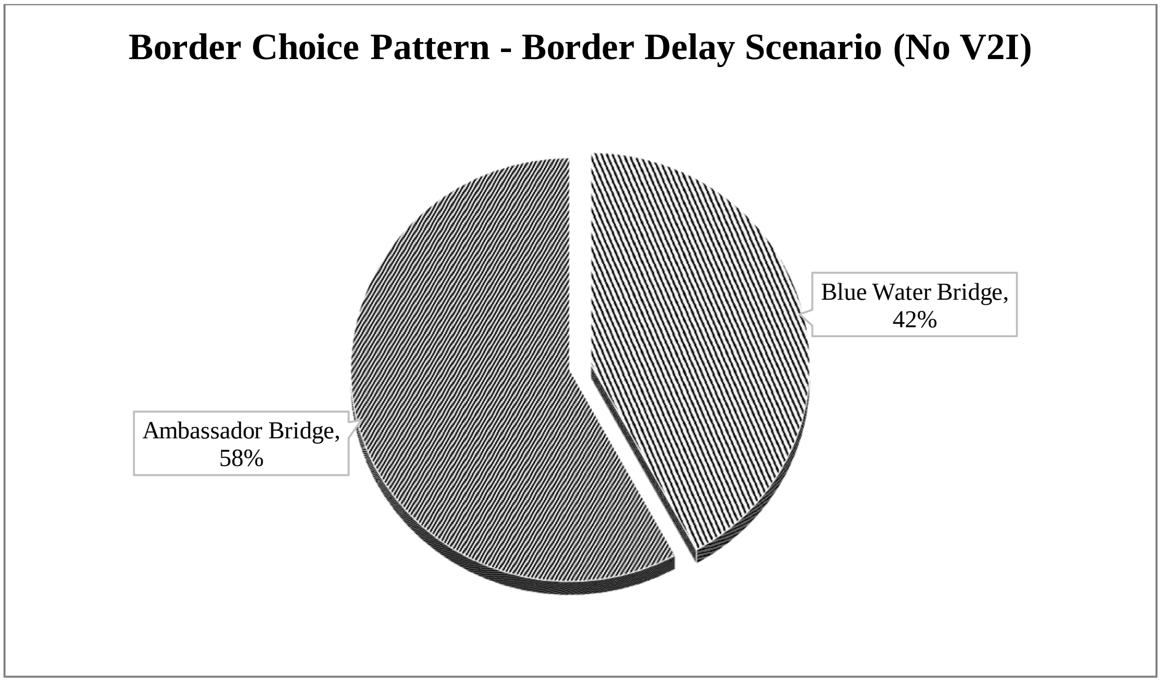


Figure 4-17 Border Choice Pattern - Border Delay and No V2I available

The border choice pattern with significant delay at the Ambassador Bridge varies slightly from the various reference datasets as well as the results from Phase 1, as presented in Figure 4-17. When Ambassador Bridge experiences an 8-hour delay in the middle of the day, the traffic patterns change, and a slightly higher percentage of traffic selects Blue Water Bridge to travel to U.S. destinations. It is expected that with an extensive delay, the DTA would assign more traffic to the less congested crossing (i.e., Blue Water Bridge).

An interesting result of this simulation scenario is the change in traffic pattern for vehicles travelling to Lansing, MI. Due to the delay at the Ambassador Bridge, all vehicles travelling to Lansing crossed the border using the Blue Water Bridge.

The travel time results for both crossings are presented in Figure 4-18 and Figure 4-19. An overall increase in travel time is observed with an 8-hour delay at the Ambassador Bridge. It can be noted that the travel time increases significantly for vehicles travelling through Ambassador Bridge whereas the travel time through Blue Water Bridge is higher but still comparable to Google Maps.

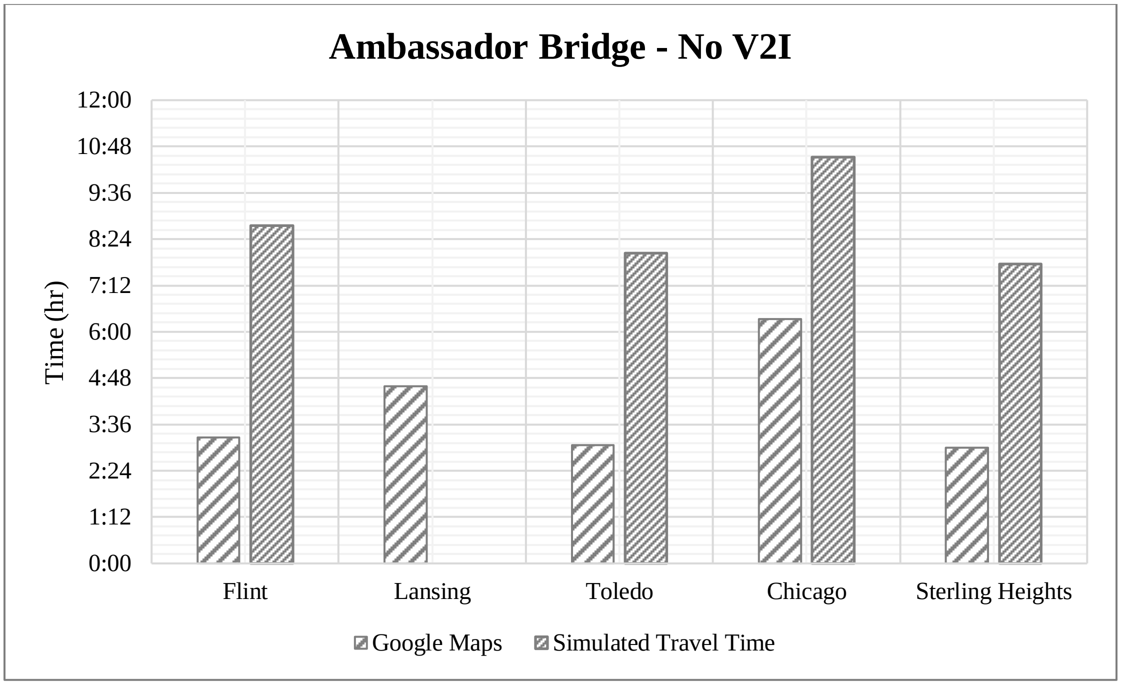


Figure 4-18 Travel Time Results for Ambassador Bridge - No V2I

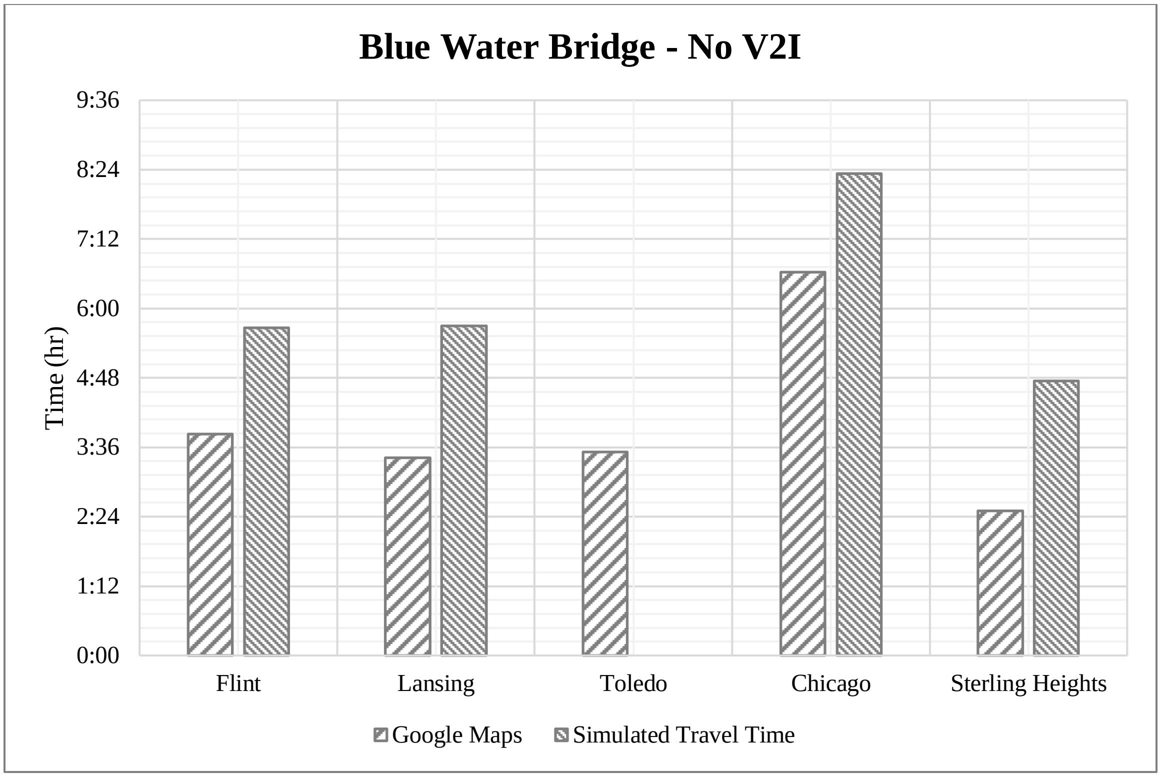


Figure 4-19 Travel Time Results for Blue Water Bridge - No V2I

The average delay experienced by vehicles travelling through Ambassador Bridge is about 5 hours. Since the simulated results are averaged over the entire 24-hour simulation, the delay is an average value. The average delay at Blue Water Bridge is 2 hours. The average delays are presented in Table 4-3.

Table 4-3 Average Delay Results for Phase III – No V2I

		Ambassador Bridge			**Blue Water Bridge**		
Origin	**Destination**	**Google Maps**	**Simulated Travel Time**	**Difference**	**Google Maps**	**Simulated Travel Time**	**Difference**
Woodstock	Flint	3:16	8:45	5:29	3:50	5:40	1:50
	Lansing	4:35	-	-	3:25	5:42	2:17
	Toledo	3:04	8:02	4:58	3:31	-	-
	Chicago	6:20	10:31	4:11	6:38	8:20	1:42
	Sterling Heights	3:00	7:45	4:45	2:30	4:45	2:15
Overall Average Delay				4:50	**Overall Average Delay**		2:01

V2I Scenario

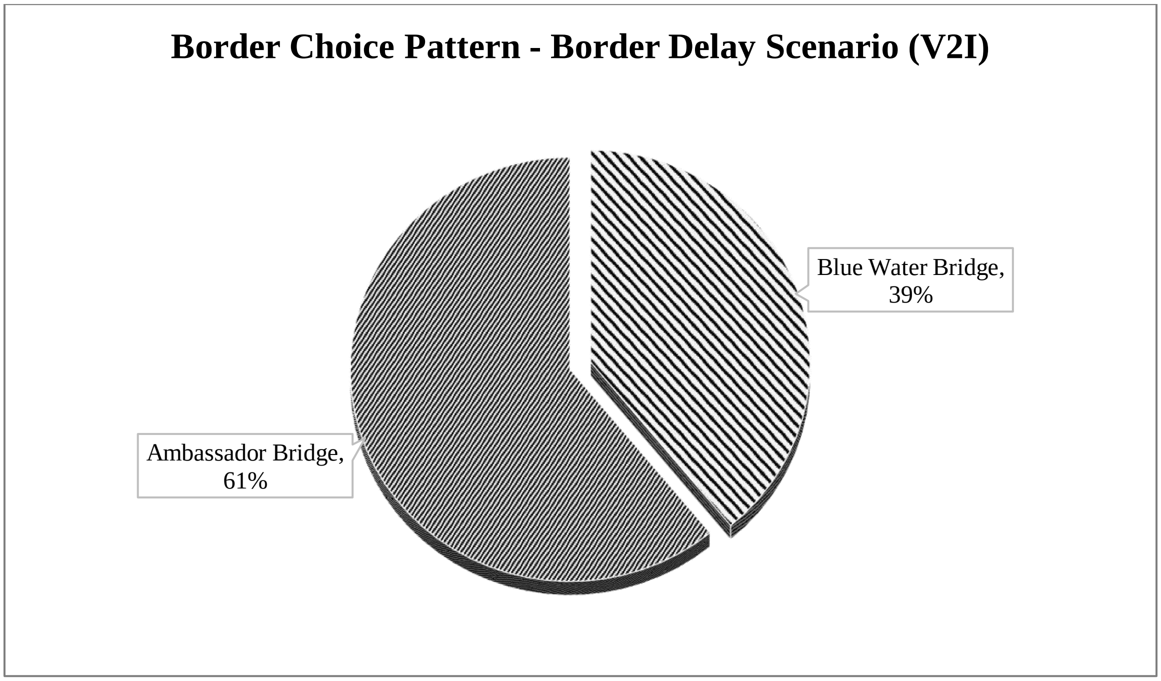


Figure 4-20 Border Choice Pattern - Border Delay with V2I

The border choice pattern in this scenario favors the Ambassador Bridge slightly more than the Blue Water Bridge, as presented in Figure 4-20. The presence of connected vehicles in this scenario could be attributed to this result. A V2I (vehicle-to-infrastructure) connection is assumed in this scenario. The delay information is transmitted to a communication infrastructure near the decision point location at the split between Highway 401 and Highway 402. As the DTA assigns routes, the connected vehicles are simultaneously communicating about the delay at the Ambassador Bridge. Even though the border patterns are not significantly different than the previous scenario, the overall delay for this case is lower. As the trucks receive information about the delay with V2I communication, they are continuously improving their route to avoid the delay, streamlining the traffic flow.

The travel time results for this scenario are presented in Figure 4-21 and Figure 4-22. An overall increase is also observed in this scenario, which is expected, but the increase is smaller in the case of Ambassador Bridge. All O-D pairs are serviced through the Ambassador Bridge in this scenario. Since there is communication between the vehicles and a communication infrastructure, the vehicles are able to change their route simultaneously with the DTA, resulting in a lower delay at the Ambassador Bridge. The trucks travelling to Toledo still travel through the Ambassador Bridge route to cross the border. The travel times through Blue Water Bridge are similar to the previous scenario.

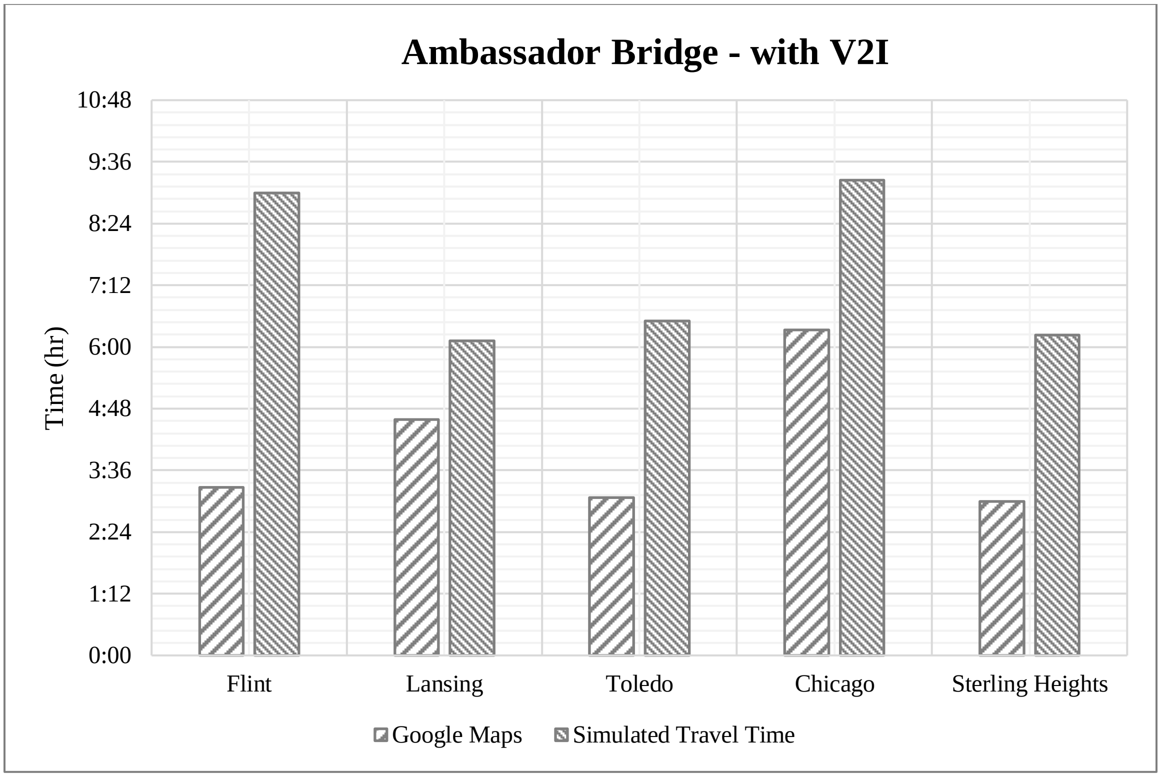


Figure 4-21 Travel Time Results for Ambassador Bridge - with V2I

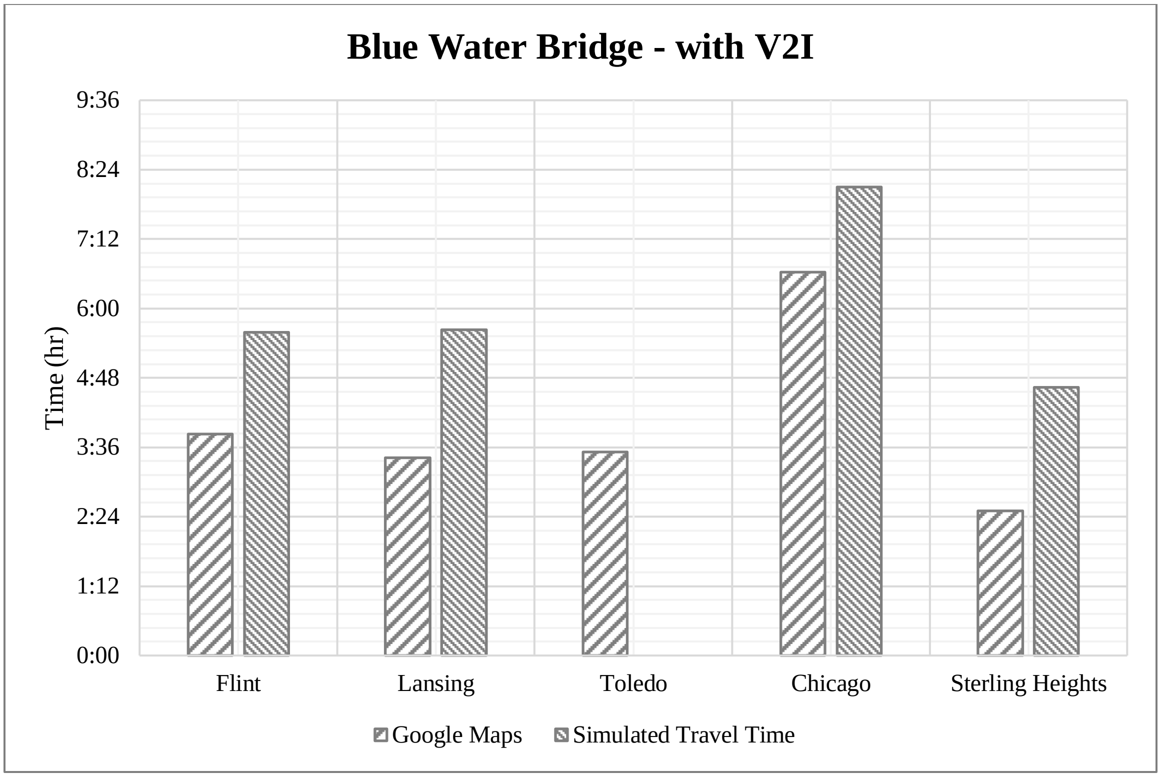


Figure 4-22 Travel Time Results for Blue Water Bridge - with V2I

The vehicles experience a lower average delay, for Ambassador Bridge. when compared to the previous scenario. The average delay results are presented in Table 4-4. The Ambassador Bridge experiences about 3.5 hours of delay whereas Blue Water Bridge still experiences about 2 hours.

Table 4-4 Average Delay Results for Phase III – with V2I

		Ambassador Bridge			**Blue Water Bridge**		
Origin	**Destination**	**Google Maps**	**Simulated Travel Time**	**Difference**	**Google Maps**	**Simulated Travel Time**	**Difference**
Woodstock	Flint	3:16	9:30	6:14	3:50	5:35	1:45
	Lansing	4:35	6:07	1:32	3:25	5:38	2:13
	Toledo	3:04	6:30	3:26	3:31	--	--
	Chicago	6:20	9:15	2:55	6:38	8:06	1:28
	Sterling Heights	3:00	6:14	3:14	2:30	4:38	2:08
Overall Average Delay				3:28	**Overall Average Delay**		1:53

5. CONCLUSION

Summary of Results

The overall objective of this thesis was to model the movement of freight trucks between Ontario, Canada and the U.S under different vehicle technology regimes. A microscopic model was developed in the software package VISSIM 10.0 to simulate the movement of individual commercial trucks between the Greater Toronto Area (GTA) and various U.S. destinations through the two international crossings: Ambassador Bridge and the Blue Water Bridge. The simulations of trucks (i.e. microsimulations) were performed using a dynamic traffic assignment application. The model was initially validated without any delays to ensure the constructed network is well integrated and to assess important network model elements such as travel time, speed, intermediate stops and preliminary border choice patterns. The network was then modeled with delays to determine how well the DTA performs as well as validate the border choice pattern against a reference dataset. The travel times for these phases were compared with measures obtained from Google Maps to determine if the chosen border crossing distributions were realistic.

Once the microsimulation model was validated with the reference datasets and the results were satisfactory, the network was then modeled with connected vehicles in the traffic stream. A sensitivity analysis was performed to determine the effect of such disruptive technology in the traffic stream. An incident was modeled just after a point where the traffic moving on Highway 401 from the GTA can either remain on highway 401 towards the Ambassador Bridge or switch to Highway 402 towards the Blue Water Bridge. The incident was introduced on Highway 401 about 200 meters past the branching point between Highways 401 and 402. Simulations were executed for a base case with no connected vehicles as well as for several connected vehicle scenarios that represent increasing penetration rates of connected vehicles in the traffic stream. The travel times along with volume were collected as a measure of performance for the network. It was evident from the results that, as the percentage of connected vehicles increased in the traffic, more trucks favoured the Blue Water Bridge to travel to various U.S. destinations.

Next, a border delay scenario was also modeled with the presence of connected vehicles to determine the efficiency of border crossing operations. The Ambassador Bridge was chosen as the border crossing experiencing extensive delays over a course of 8 hours. A base case was modeled to examine the border choice patterns as well as the average travel time for the modeled O-D pairs. A V2I scenario was modeled with vehicles receiving the information about the delay before the decision point near Highways 401 and 402. Connected vehicles receiving the information can then make a decision to stay course on Highway 401 or switch route to Highway 402 to reach their destination in the U.S. The base case scenario experienced an overall delay of 5 hours at the Ambassador Bridge whereas the V2I scenario experienced 3.5 hours.

Contributions and Policy Implications

The study makes four distinct contributions to the area of cross-border traffic analysis:

1. Implementation of a regional cross-border microsimulation network.
2. Introduction and application of a methodology on developing O-D matrices for freight trucks as well as passenger vehicles using various datasets.
3. Application of a dynamic traffic assignment in a cross-border route choice context.

4. Analysis of connected vehicles (namely: V2V and V2I) on border crossing operations.

The potential of microsimulations and their applications are highlighted in this study. A regional model can be analyzed in a realistic microsimulation environment without spending countless hours in the field. The use of passive GPS data, as well as other data sources, bolsters the quality of the analysis and further verifies the effectiveness of VISSIM's DTA application.

The implementation of disruptive technology encourages policy makers to start an informed conversation about the benefits of such emerging technology in the context of cross-border traffic. Since the technology has already been introduced in various parts of the world, it is only a matter of time for it to become part of cross-border traffic. Government support and incentives could encourage automotive manufacturers to invest in improving the V2V technology and making it accessible to the public. Also, investments in V2I technology will be needed to facilitate the adoption of connected vehicles in Canada. The governments of Canada and the U.S. will also need to define regulations for connected vehicles in the cross-border context and these regulations would further be refined by building and expanding the type of research conducted in this thesis.

Study Limitations and Direction for Future Development

Dynamic Traffic Assignment Module

The DTA module in VISSIM can be adjusted according to network requirements, convergence criterion, route choice model, cost calculations, and such. The large extent of the network and the time required to execute a complete simulation for a given scenario (approximately 5-6 days, 140 hours) did not allow for the testing of too many scenarios within the module. The simulation time doubled in the V2V scenarios as the execution of the Python code within the simulation required more time. The standard settings were used for this study. A smaller road network would be ideal to determine the combination of settings for the required objective of a study. The module should be further tested for optimal route searching conditions, cost calculations and such depending on the requirement of the research being done.

VISSIM Road Network

The road network in the study mainly consisted of highways between the O-D pairs representing commercial truck traffic between Ontario and key Western U.S. destinations. The network excluded some of local network links in Windsor, ON (e.g., traffic from EC Row Expressway) since the focus of the analysis was regional O-D pairs. Furthermore, due to the time-intensive nature of accurately adding road links to the network, it was deemed unnecessary for this study. However, the addition of urban road links to the model can provide more accuracy to the DTA results.

Connected Vehicles

The implementation of connected vehicles with a DTA module within VISSIM is a novel approach. VISSIM's limited functionality in modeling connected vehicles also introduced unforeseen challenges during the course of this research. A basic Python code provided with VISSIM's training files was applicable to a static case only (i.e. no route choice). The code was modified to run under a DTA in which route choices take place. However, the modifications were applied to handle one class of connected vehicles in the simulations (i.e., commercial trucks). The code could be further updated to account for different classes of connected vehicles within the DTA.

The effects of connected vehicles in the traffic stream were more pronounced in the demo network than the regional model. The location of the incident, the extent of the model, and the presence of multiple destinations in the regional model all played a role in the achieved results.

Additional Recommendations for Future Work

This model provides a novel approach for performing regional cross-border analysis using microsimulation models. The expansion of the local road network will improve the route search algorithm and allow the DTA module to search for more realistic routes between the O-D pairs. The addition of other border crossings in Ontario (e.g. Peace Bridge and Queenston Lewiston Bridge) as well as other O-D pairs would also add to the field of study. The model can also be used to perform queue analysis at the border crossings as well performing emission modelling from the idling vehicles under different V2V/V2I regimes.

An interesting application for future research would be to add the Gordie Howe International Bridge (GHIB), the new border crossing currently under construction in Windsor, ON, to the network to model and analyze the traffic patterns as well as the effects of connected vehicles. The proximity of the GHIB to the Ambassador Bridge would result in a different border crossing pattern than the existing ones. It would be interesting to observe the patterns in the delay scenario at the Ambassador Bridge with the decision point in close proximity to the border crossings. Also, a toll analysis would be beneficial to determine favourable conditions for both crossings as well as a break-even point

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APPENDIX A: TRIP CHAIN FILES

Table A-1 Trip Chain File for Demo Network

Version	1.1									
Vehicle #	Vehicle Type	Origin Zone	Departure Time	Intermediate Destination Zone	Activity	Minimum Dwell Time	Departure Time	Destination Zone	Activity	Minimum Dwell Time
1001	100	1	200	3	101	1250	1000	2	102	0

Table A-2 Trip Chain File for Traffic Analysis Phase II

Version	1.1									
Vehicle #	Vehicle Type	Origin Zone	Departure Time	Intermediate Destination Zone	Activity	Minimum Dwell Time	Departure Time	Destination Zone	Activity	Minimum Dwell Time
1001	200	1	28800	17	101	22000	1000	14	102	0

Table A-3 Trip Chain File for Traffic Analysis Phase III

Version	1.1									
Vehicle #	Vehicle Type	Origin Zone	Departure Time	Intermediate Destination Zone	Activity	Minimum Dwell Time	Departure Time	Destination Zone	Activity	Minimum Dwell Time
1001	101	16	24600	17	101	30600	1000	6	102	0
1002	101	16	25800	18	101	31800	1000	6	102	0
1003	101	16	27000	19	101	33000	1000	6	102	0
1004	101	16	28200	20	101	34200	1000	6	102	0
1005	101	16	29400	21	101	35400	1000	6	102	0
1006	101	16	30600	22	101	36600	1000	6	102	0

APPENDIX B:PYTHON CODE

This section presents the original Python code available in the VISSIM training files as well as the modified Python code used in the connected vehicle scenarios. The underlined and bolded code presents the modified sections to be implemented with the DTA in VISSIM.

Python Code (Original Code available in VISSIM)

```
# This Car2X (C2X) example demonstrates how to model communication between vehicles.

# At simulation second 200, there is a breakdown of a vehicle. At the time of breakdown, the vehicle sends out a warning message.

# Vehicles receiving this message will drop their speed and adjust their driving behavior until they passed the incident.


def Initialization():

    # Global Parameters:

    global distDistr

    global Vehicle_Type_C2X_no_message

    global Vehicle_Type_C2X_HasCurrentMessage

    global speed_incident
```

```
    distDistr = 1 # number of Distance distribution used for sending out a C2X message
    Vehicle_Type_C2X_no_message = '101' # number of C2X vehicle type (no active message) has to be a string!
    Vehicle_Type_C2X_HasCurrentMessage = '102' # number of C2X vehicle type with active message has to be a string!
    speed_incident = 80 # Speed of vehicles receiving the C2X message in kph
    return


def Main():
    # Get several attributes of all vehicles:
    Veh_attributes = Vissim.Net.Vehicles.GetMultipleAttributes(('RoutDecType', 'RoutDecNo', 'VehType', 'No'))
    if len(Veh_attributes) > 0: # Check if there are any vehicles in the network:
        # Filter by VehType C2X:
        Veh_C2X_attributes = [item for item in Veh_attributes if item[2] == Vehicle_Type_C2X_no_message or item[2] == Vehicle_Type_C2X_HasCurrentMessage]
```

```
    # For all C2X vehicles: check if there is an incident | incident is modelled as parking routing decision #1
    for cnt_C2X_veh in range(len(Veh_C2X_attributes)):
        if Veh_C2X_attributes[cnt_C2X_veh][0] == 'PARKING' and Veh_C2X_attributes[cnt_C2X_veh][1] == 1: # vehicle has an incident (parking routing decision #1)
            Veh_sending_Msg = Vissim.Net.Vehicles.ItemByKey(Veh_C2X_attributes[cnt_C2X_veh][3])
            Coord_Veh = Veh_sending_Msg.AttValue('CoordFront') # reading the world coordinates (x y z) of the vehicle
            PositionXYZ = Coord_Veh.split(" ")
            Pos_Veh_SM = Veh_sending_Msg.AttValue('Pos') # relative position on the current link
            Veh_sending_Msg.SetAttValue('C2X_HasCurrentMessage', 1)
            Veh_sending_Msg.SetAttValue('C2X_SendingMessage', 1)
            Veh_sending_Msg.SetAttValue('C2X_MessageOrigin', Pos_Veh_SM)
            # Getting vehicles which receive the message:
            Veh_Rec_Message = Vissim.Net.Vehicles.GetByLocation(PositionXYZ[0], PositionXYZ[1], distDistr)
```

```
# Reading Attribute of all Vehicles who are receiving the C2X message (Note: all vehicle classes involved, also non C2X vehicles)
Attributes = ('Pos', 'VehType', 'C2X_HasCurrentMessage', 'C2X_MessageOrigin', 'C2X_Message', 'DesSpeed', 'C2X_DesSpeedOld')
Veh_attributes_Rec_Message = list(Veh_Rec_Message.GetMultipleAttributes(Attributes))
# Adjusting the attributes of the C2X vehicles because of this message:
for cnt_Veh_Rec_Message in range(len(Veh_attributes_Rec_Message)):
    atts_current = Veh_attributes_Rec_Message[cnt_Veh_Rec_Message]
    pos_cur = atts_current[0]
    veh_type_cur = atts_current[1]
    pos_C2X_cur = atts_current[3]
    des_speed_cur = atts_current[5]
    des_speed_old_cur = atts_current[6]
    if (veh_type_cur == Vehicle_Type_C2X_no_message or veh_type_cur == Vehicle_Type_C2X_HasCurrentMessage) and pos_cur < Pos_Veh_SM and Pos_Veh_SM > pos_C2X_cur: # check if vehicle has C2X & position of C2X message is downstream & there is no other further downstream message active
        if des_speed_cur == speed_incident:
```

```
                            # if the attribute 'DesSpeed' was already set to 'speed_incident', don't
overwrite 'C2X_DesSpeedOld' with current 'DesSpeed' = 'speed_incident'
                            Veh_attributes_Rec_Message[cnt_Veh_Rec_Message] =
tuple([int(Vehicle_Type_C2X_HasCurrentMessage), 1, Pos_Veh_SM, 'Breakdown
Vehicle ahead!', speed_incident, des_speed_old_cur])
                        else:
                            Veh_attributes_Rec_Message[cnt_Veh_Rec_Message] =
tuple([int(Vehicle_Type_C2X_HasCurrentMessage), 1, Pos_Veh_SM, 'Breakdown
Vehicle ahead!', speed_incident, des_speed_cur])
                    else:
                        Veh_attributes_Rec_Message[cnt_Veh_Rec_Message] = atts_current[1:]
# no changes, vehicle has no C2X or is not affected due to the position
                # Giving back the adjusted attributes to Vissim (note: attribute 'Pos' is read-
only)
                Veh_Rec_Message.SetMultipleAttributes(Attributes[1:],
Veh_attributes_Rec_Message)
        # Check if vehicles with active message passed the position of the warning message:
        Attributes = ('Pos', 'VehType', 'C2X_HasCurrentMessage', 'C2X_MessageOrigin',
'C2X_Message', 'DesSpeed', 'C2X_DesSpeedOld')
        Veh_attributes = list(Vissim.Net.Vehicles.GetMultipleAttributes(Attributes))
```

```
        for cnt_Veh in range(len(Veh_attributes)):
            atts_current = Veh_attributes[cnt_Veh]
            pos_cur = atts_current[0]
            veh_type_cur = atts_current[1]
            C2X_msg_active_cur = atts_current[2]
            pos_C2X_cur = atts_current[3]
            des_speed_old_cur = atts_current[6]
            # if the vehicle has an active C2X message AND the position is larger than the C2X Position
            if C2X_msg_active_cur == 1 and pos_cur > pos_C2X_cur:
                Veh_attributes[cnt_Veh] = [int(Vehicle_Type_C2X_no_message), 0, '', '', des_speed_old_cur, '']
            else:
                Veh_attributes[cnt_Veh] = atts_current[1:] # no changes
            # Returning the adjusted attributes to Vissim (note: attribute 'Pos' is read-only)
        Vissim.Net.Vehicles.SetMultipleAttributes(Attributes[1:], Veh_attributes)
    return
```

Python Code (Modified Code)

```
# This Car2X (C2X) example demonstrates how to model communication between vehicles.
# At the time of breakdown, the vehicle sends out a warning message.
# Vehicles receiving this message will drop their speed and adjust their driving behavior until they passed the incident.

def Initialization():
    # Global Parameters:
    global distDistr
    global Vehicle_Type_C2X_no_message
    global Vehicle_Type_C2X_HasCurrentMessage
    global speed_incident

    distDistr = 1 # number of Distance distribution used for sending out a C2X message
    Vehicle_Type_C2X_no_message = '101' # number of C2X vehicle type (no active message) has to be a string!
    Vehicle_Type_C2X_HasCurrentMessage = '102' # number of C2X vehicle type with active message has to be a string!
    speed_incident = 100 # Speed of vehicles receiving the C2X message in kph
    return
def Main():
```

```
    # Get several attributes of all vehicles:
    Veh_attributes = Vissim.Net.Vehicles.GetMultipleAttributes(('RoutDecType',
'RoutDecNo', 'VehType', 'No', 'CurParkLot'))


    if len(Veh_attributes) > 0: # Check if there are any vehicles in the network:
        # Filter by VehType C2X:
        Veh_C2X_attributes = [item for item in Veh_attributes if item[2] ==
Vehicle_Type_C2X_no_message or item[2] ==
Vehicle_Type_C2X_HasCurrentMessage]
        # For all C2X vehicles: check if there is an incident | incident is modelled as parking
routing decision #1
        for cnt_C2X_veh in range(len(Veh_C2X_attributes)):
            if Veh_C2X_attributes[cnt_C2X_veh][4] == '25':
                Veh_sending_Msg =
Vissim.Net.Vehicles.ItemByKey(Veh_C2X_attributes[cnt_C2X_veh][3])
                Coord_Veh = Veh_sending_Msg.AttValue('CoordFront') # reading the world
coordinates (x y z) of the vehicle
                        if Coord_Veh is None:
continue
                PositionXYZ = Coord_Veh.split(" ")
                Pos_Veh_SM = Veh_sending_Msg.AttValue('Pos') # relative position on the
current link
                Veh_sending_Msg.SetAttValue('C2X_HasCurrentMessage', 3)
```

```
        Veh_sending_Msg.SetAttValue('C2X_SendingMessage', 3)

        Veh_sending_Msg.SetAttValue('C2X_MessageOrigin', Pos_Veh_SM)

        # Getting vehicles which receive the message:

        Veh_Rec_Message = Vissim.Net.Vehicles.GetByLocation(PositionXYZ[0], PositionXYZ[1], distDistr)

        # Reading Attribute of all Vehicles who are receiving the C2X message (Note: all vehicle classes involved, also non C2X vehicles)

        Attributes = ('Pos', 'VehType', 'C2X_HasCurrentMessage', 'C2X_MessageOrigin', 'C2X_Message', 'DesSpeed', 'C2X_DesSpeedOld')

        Veh_attributes_Rec_Message = list(Veh_Rec_Message.GetMultipleAttributes(Attributes))

        # Adjusting the attributes of the C2X vehicles because of this message:

        for cnt_Veh_Rec_Message in range(len(Veh_attributes_Rec_Message)):

            atts_current = Veh_attributes_Rec_Message[cnt_Veh_Rec_Message]

            pos_cur = atts_current[0]

            veh_type_cur = atts_current[1]

            pos_C2X_cur = atts_current[3]

            des_speed_cur = atts_current[5]

            des_speed_old_cur = atts_current[6]

            if pos_cur is not None and (veh_type_cur == Vehicle_Type_C2X_no_message or veh_type_cur == Vehicle_Type_C2X_HasCurrentMessage) and pos_cur < Pos_Veh_SM and Pos_Veh_SM > pos_C2X_cur: # check if vehicle has C2X & position of C2X message is downstream & there is no other further downstream message active
```

```
                    if des_speed_cur == speed_incident:
                        # if the attribute 'DesSpeed' was already set to 'speed_incident', don't overwrite 'C2X_DesSpeedOld' with current 'DesSpeed' = 'speed_incident'
                        Veh_attributes_Rec_Message[cnt_Veh_Rec_Message] = tuple([int(Vehicle_Type_C2X_HasCurrentMessage), 1, Pos_Veh_SM, 'Breakdown Vehicle ahead!', speed_incident, des_speed_old_cur])
                    else:
                        Veh_attributes_Rec_Message[cnt_Veh_Rec_Message] = tuple([int(Vehicle_Type_C2X_HasCurrentMessage), 1, Pos_Veh_SM, 'Breakdown Vehicle ahead!', speed_incident, des_speed_cur])
                else:
                    Veh_attributes_Rec_Message[cnt_Veh_Rec_Message] = atts_current[1:] # no changes, vehicle has no C2X or is not affected due to the position
            # Giving back the adjusted attributes to Vissim (note: attribute 'Pos' is read-only)
            Veh_Rec_Message.SetMultipleAttributes(Attributes[1:], Veh_attributes_Rec_Message)
    # Check if vehicles with active message passed the position of the warning message:
    Attributes = ('Pos', 'VehType', 'C2X_HasCurrentMessage', 'C2X_MessageOrigin', 'C2X_Message', 'DesSpeed', 'C2X_DesSpeedOld')
    Veh_attributes = list(Vissim.Net.Vehicles.GetMultipleAttributes(Attributes))
    for cnt_Veh in range(len(Veh_attributes)):
        atts_current = Veh_attributes[cnt_Veh]
        pos_cur = atts_current[0]
```

```
            veh_type_cur = atts_current[1]
            C2X_msg_active_cur = atts_current[2]
            pos_C2X_cur = atts_current[3]
            des_speed_old_cur = atts_current[6]
            # if the vehicle has an active C2X message AND the position is larger than the C2X Position
            if C2X_msg_active_cur == 1 and pos_cur > pos_C2X_cur:
                Veh_attributes[cnt_Veh] = [int(Vehicle_Type_C2X_no_message), 0, ", ", des_speed_old_cur, "]
            else:
                Veh_attributes[cnt_Veh] = atts_current[1:] # no changes
            # Returning the adjusted attributes to Vissim (note: attribute 'Pos' is read-only)
        Vissim.Net.Vehicles.SetMultipleAttributes(Attributes[1:], Veh_attributes)
    return
```

APPENDIX C: DEVELOPMENT OF O-D MATRICES

This appendix outlines the data used to develop the O-D matrices required for the VISSIM model. Table C-1 presents the weekday hourly breakdown for passenger vehicles and trucks for the Ambassador Bridge and Table C-2 presents the same for Blue Water Bridge.

Table C-1: CVS Weekday Hourly Breakdown for Ambassador Bridge

Hour	**Hourly Crossing Percentage**	**Passenger Vehicles**	**Hourly Crossing Percentage**	**Freight Trucks**
0	0.022	141	0.032	161
1	0.022	146	0.027	136
2	0.016	105	0.026	130
3	0.012	77	0.027	137
4	0.011	73	0.034	169
5	0.027	175	0.039	194
6	0.073	472	0.040	198
7	0.109	710	0.044	218
8	0.079	511	0.051	255
9	0.051	334	0.055	274
10	0.043	279	0.051	256
11	0.041	265	0.053	264
12	0.044	283	0.054	270
13	0.045	295	0.052	261
14	0.052	338	0.049	243
15	0.050	328	0.048	239
16	0.049	318	0.046	228
17	0.046	300	0.047	233
18	0.046	298	0.044	218
19	0.037	240	0.043	214
20	0.033	215	0.037	185
21	0.030	193	0.038	189
22	0.034	224	0.034	171
23	0.027	175	0.031	157
Total		**6495**		**5000**

Table C-2: CVS Weekday Hourly Breakdown for Blue Water Bridge

Hour	**Hourly Crossing Percentage**	**Passenger Vehicles**	**Hourly Crossing Percentage**	**Freight Trucks**
0	0.023	90	0.031	69
1	0.008	31	0.027	24
2	0.014	55	0.024	42
3	0.003	10	0.033	8
4	0.005	18	0.037	14
5	0.014	57	0.039	44
6	0.031	122	0.044	94
7	0.039	157	0.043	121
8	0.045	181	0.046	139
9	0.049	197	0.053	152
10	0.060	238	0.043	183
11	0.063	250	0.047	192
12	0.062	246	0.044	190
13	0.071	283	0.042	218
14	0.070	279	0.042	215
15	0.076	303	0.045	233
16	0.066	262	0.057	201
17	0.059	237	0.044	182
18	0.063	252	0.048	194
19	0.047	188	0.046	145
20	0.035	141	0.044	109
21	0.049	196	0.042	151
22	0.030	118	0.044	90
23	0.017	69	0.036	53
Total		**3980**		**3063**

Table C-3 RTMS Data for Trucks for the Ambassador Bridge (U.S.-Bound)

Hour	**Matrix**	**Hourly Truck Total**	**15-min interval Truck Trips**	**Trip Percentage of Hour**
0	1	87	15	0.172
	2		22	0.253
	3		25	0.287
	4		25	0.287
1	5	79	24	0.304
	6		17	0.215
	7		26	0.329
	8		12	0.152
2	9	122	35	0.287
	10		19	0.156
	11		35	0.287
	12		33	0.270
3	13	150	33	0.220
	14		39	0.260
	15		38	0.253
	16		40	0.267
4	17	187	45	0.241
	18		37	0.198
	19		52	0.278
	20		53	0.283
5	21	249	60	0.241
	22		74	0.297
	23		49	0.197
	24		66	0.265
6	25	276	51	0.185
	26		86	0.312
	27		60	0.217
	28		79	0.286
7	29	239	60	0.251
	30		65	0.272
	31		42	0.176
	32		72	0.301
8	33	222	56	0.252
	34		43	0.194
	35		56	0.252

	36		67	0.302
9	37	246	54	0.220
	38		66	0.268
	39		69	0.280
	40		57	0.232
10	41	227	57	0.251
	42		47	0.207
	43		61	0.269
	44		62	0.273
11	45	235	48	0.204
	46		68	0.289
	47		58	0.247
	48		61	0.260
12	49	207	44	0.213
	50		33	0.159
	51		55	0.266
	52		75	0.362
13	53	239	60	0.251
	54		59	0.247
	55		54	0.226
	56		66	0.276
14	57	261	59	0.226
	58		64	0.245
	59		65	0.249
	60		73	0.280
15	61	250	67	0.268
	62		57	0.228
	63		61	0.244
	64		65	0.260
16	65	270	74	0.274
	66		69	0.256
	67		60	0.222
	68		67	0.248
17	69	205	40	0.195
	70		48	0.234
	71		64	0.312
	72		53	0.259
18	73	214	54	0.252
	74		57	0.266

	75		65	0.304
	76		38	0.178
19	77	211	42	0.199
	78		63	0.299
	79		53	0.251
	80		53	0.251
20	81	163	47	0.288
	82		47	0.288
	83		37	0.227
	84		32	0.196
21	85	135	31	0.230
	86		40	0.296
	87		36	0.267
	88		28	0.207
22	89	152	40	0.263
	90		43	0.283
	91		32	0.211
	92		37	0.243
23	93	104	22	0.212
	94		27	0.260
	95		25	0.240
	96		30	0.288

Table C-4 RTMS Data for Passenger Vehicles for Ambassador Bridge (U.S.-Bound)

Hour	**Matrix**	**Hourly Car Total**	**Hourly Car Trips**	**Percentage of Hour**
0	1	13	2	0.154
	2		3	0.231
	3		3	0.231
	4		5	0.385
1	5	6	3	0.500
	6		1	0.167
	7		2	0.333
	8		0	0.000
2	9	13	3	0.231
	10		0	0.000
	11		3	0.231
	12		7	0.538
3	13	22	5	0.227
	14		7	0.318
	15		6	0.273
	16		4	0.182
4	17	79	13	0.165
	18		17	0.215
	19		22	0.278
	20		27	0.342
5	21	152	33	0.217
	22		46	0.303
	23		36	0.237
	24		37	0.243
6	25	175	45	0.257
	26		41	0.234
	27		42	0.240
	28		47	0.269
7	29	128	36	0.281
	30		35	0.273
	31		30	0.234
	32		27	0.211
8	33	90	18	0.200
	34		23	0.256
	35		21	0.233
	36		28	0.311

9	37	85	22	0.259
	38		24	0.282
	39		20	0.235
	40		19	0.224
10	41	95	20	0.211
	42		29	0.305
	43		16	0.168
	44		30	0.316
11	45	100	22	0.220
	46		20	0.200
	47		15	0.150
	48		43	0.430
12	49	90	15	0.167
	50		33	0.367
	51		19	0.211
	52		23	0.256
13	53	91	29	0.319
	54		14	0.154
	55		28	0.308
	56		20	0.220
14	57	98	28	0.286
	58		21	0.214
	59		23	0.235
	60		26	0.265
15	61	103	26	0.252
	62		18	0.175
	63		31	0.301
	64		28	0.272
16	65	101	26	0.257
	66		30	0.297
	67		19	0.188
	68		26	0.257
17	69	85	17	0.200
	70		26	0.306
	71		22	0.259
	72		20	0.235
18	73	83	24	0.289
	74		20	0.241
	75		20	0.241

	76		19	0.229
19	77	66	14	0.212
	78		18	0.273
	79		17	0.258
	80		17	0.258
20	81	41	9	0.220
	82		12	0.293
	83		10	0.244
	84		10	0.244
21	85	37	12	0.324
	86		5	0.135
	87		10	0.270
	88		10	0.270
22	89	32	16	0.500
	90		4	0.125
	91		5	0.156
	92		7	0.219
23	93	12	3	0.250
	94		3	0.250
	95		3	0.250
	96		3	0.250

Table C-5 CVS Data (Processed) Arrival Rate for the Ambassador Bridge

Hour	**Matrix**	**Passenger Vehicle Hourly Totals**	**Passenger Vehicle Trips per 15-min interval**	**Truck Hourly Total**	**Truck Trips per 15-minute interval**
0	1	141	22	161	28
	2		32		41
	3		32		46
	4		54		46
1	5	146	73	136	41
	6		24		29
	7		49		45
	8		0		21
2	9	105	24	130	37
	10		0		20
	11		24		37
	12		57		35
3	13	77	17	137	30
	14		24		36
	15		21		35
	16		14		37
4	17	73	12	169	41
	18		16		33
	19		20		47
	20		25		48
5	21	175	38	194	47
	22		53		58
	23		41		38
	24		43		51
6	25	472	121	198	37
	26		111		62
	27		113		43
	28		127		57
7	29	710	200	218	55
	30		194		59
	31		166		38
	32		150		66
8	33	511	102	255	64

	34		131		49
	35		119		64
	36		159		77
9	37	334	87	274	60
	38		94		73
	39		79		77
	40		75		63
10	41	279	59	256	64
	42		85		53
	43		47		69
	44		88		70
11	45	265	58	264	54
	46		53		76
	47		40		65
	48		114		69
12	49	283	47	270	57
	50		104		43
	51		60		72
	52		72		98
13	53	295	94	261	65
	54		45		64
	55		91		59
	56		65		72
14	57	338	97	243	55
	58		73		60
	59		79		61
	60		90		68
15	61	328	83	239	64
	62		57		55
	63		99		58
	64		89		62
16	65	318	82	228	62
	66		94		58
	67		60		51
	68		82		57
17	69	300	60	233	45
	70		92		54
	71		78		73
	72		71		60

18	73	298	86	218	55
	74		72		58
	75		72		66
	76		68		39
19	77	240	51	214	43
	78		65		64
	79		62		54
	80		62		54
20	81	215	47	185	53
	82		63		53
	83		52		42
	84		52		36
21	85	193	63	189	43
	86		26		56
	87		52		50
	88		52		39
22	89	224	112	171	45
	90		28		48
	91		35		36
	92		49		42
23	93	175	44	157	33
	94		44		41
	95		44		38
	96		44		45

Table C-6 CVS Data (Processed) Arrival Rates for the Blue Water Bridge

Hour	**Matrix**	**Passenger Vehicle Hourly Totals**	**Passenger Vehicle Trips per 15-min interval**	**Truck Hourly Total**	**Truck Trips per 15-minute interval**
0	1	90	14	69	12
	2		21		18
	3		21		20
	4		35		20
1	5	31	16	24	7
	6		5		5
	7		10		8
	8		0		4
2	9	55	13	42	12
	10		0		7
	11		13		12
	12		30		11
3	13	10	2	8	2
	14		3		2
	15		3		2
	16		2		2
4	17	18	3	14	3
	18		4		3
	19		5		4
	20		6		4
5	21	57	12	44	11
	22		17		13
	23		14		9
	24		14		12
6	25	122	31	94	17
	26		29		29
	27		29		20
	28		33		27
7	29	157	44	121	30
	30		43		33
	31		37		21
	32		33		36
8	33	181	36	139	35

	34		46		27
	35		42		35
	36		56		42
9	37	197	51	152	33
	38		56		41
	39		46		43
	40		44		35
10	41	238	50	183	46
	42		73		38
	43		40		49
	44		75		50
11	45	250	55	192	39
	46		50		56
	47		37		47
	48		107		50
12	49	246	41	190	40
	50		90		30
	51		52		50
	52		63		69
13	53	283	90	218	55
	54		44		54
	55		87		49
	56		62		60
14	57	279	80	215	49
	58		60		53
	59		66		54
	60		74		60
15	61	303	77	233	63
	62		53		53
	63		91		57
	64		82		61
16	65	262	67	201	55
	66		78		51
	67		49		45
	68		67		50
17	69	237	47	182	36
	70		72		43
	71		61		57
	72		56		47

18	73	252	73	194	49
	74		61		52
	75		61		59
	76		58		34
19	77	188	40	145	29
	78		51		43
	79		48		36
	80		48		36
20	81	141	31	109	31
	82		41		31
	83		34		25
	84		34		21
21	85	196	64	151	35
	86		27		45
	87		53		40
	88		53		31
22	89	118	59	90	24
	90		15		26
	91		18		19
	92		26		22
23	93	69	17	53	11
	94		17		14
	95		17		13
	96		17		15

Table C-7 Total Truck Volume – 15-minute intervals

Matrix #	**Hour**	**Ambassador Bridge**	**Blue Water Bridge**	**Total Trucks**
1	0	28	12	**40**
2		41	18	**58**
3		46	20	**66**
4		46	20	**66**
5	1	41	7	**49**
6		29	5	**35**
7		45	8	**53**
8		21	4	**24**
9	2	37	12	**50**
10		20	7	**27**
11		37	12	**50**
12		35	11	**47**
13	3	30	2	**32**
14		36	2	**38**
15		35	2	**37**
16		37	2	**39**
17	4	41	3	**44**
18		33	3	**36**
19		47	4	**51**
20		48	4	**52**
21	5	47	11	**57**
22		58	13	**71**
23		38	9	**47**
24		51	12	**63**
25	6	37	17	**54**
26		62	29	**91**
27		43	20	**64**
28		57	27	**84**
29	7	55	30	**85**
30		59	33	**92**
31		38	21	**60**
32		66	36	**102**
33	8	64	35	**99**
34		49	27	**76**
35		64	35	**99**
36		77	42	**119**

37	9	60	33	**93**
38		73	41	**114**
39		77	43	**119**
40		63	35	**99**
41	10	64	46	**110**
42		53	38	**91**
43		69	49	**118**
44		70	50	**120**
45	11	54	39	**93**
46		76	56	**132**
47		65	47	**113**
48		69	50	**118**
49	12	57	40	**98**
50		43	30	**73**
51		72	50	**122**
52		98	69	**166**
53	13	65	55	**120**
54		64	54	**118**
55		59	49	**108**
56		72	60	**132**
57	14	55	49	**104**
58		60	53	**112**
59		61	54	**114**
60		68	60	**128**
61	15	64	63	**127**
62		55	53	**108**
63		58	57	**115**
64		62	61	**123**
65	16	62	55	**118**
66		58	51	**110**
67		51	45	**95**
68		57	50	**107**
69	17	45	36	**81**
70		54	43	**97**
71		73	57	**129**
72		60	47	**107**
73	18	55	49	**104**
74		58	52	**110**
75		66	59	**125**

76		39	34	**73**
77	19	43	29	**71**
78		64	43	**107**
79		54	36	**90**
80		54	36	**90**
81	20	53	31	**85**
82		53	31	**85**
83		42	25	**67**
84		36	21	**58**
85	21	43	35	**78**
86		56	45	**101**
87		50	40	**91**
88		39	31	**70**
89	22	45	24	**69**
90		48	26	**74**
91		36	19	**55**
92		42	22	**64**
93	23	33	11	**44**
94		41	14	**54**
95		38	13	**50**
96		45	15	**61**

Table C-8 Volume Breakdown for each Destination - Trucks

Matrix	**Hour**	**47%**	**17%**	**6%**	**3%**	**27%**	**Total**
		Toledo	**Chicago**	**Lansing**	**Flint**	**Sterling Heights**	
1	0	19	7	2	1	11	**40**
2		27	10	3	2	16	**58**
3		31	11	4	2	18	**66**
4		31	11	4	2	18	**66**
5	1	23	8	3	1	13	**49**
6		16	6	2	1	9	**35**
7		25	9	3	2	14	**53**
8		11	4	1	1	7	**24**
9	2	23	8	3	1	13	**50**
10		13	5	2	1	7	**27**
11		23	8	3	1	13	**50**
12		22	8	3	1	13	**47**
13	3	15	5	2	1	9	**32**
14		18	6	2	1	10	**38**
15		17	6	2	1	10	**37**
16		18	7	2	1	11	**39**
17	4	21	8	3	1	12	**44**
18		17	6	2	1	10	**36**
19		24	9	3	2	14	**51**
20		24	9	3	2	14	**52**
21	5	27	10	3	2	16	**57**
22		33	12	4	2	19	**71**
23		22	8	3	1	13	**47**
24		29	11	4	2	17	**63**
25	6	25	9	3	2	15	**54**
26		43	16	5	3	25	**91**
27		30	11	4	2	17	**64**
28		39	14	5	3	23	**84**
29	7	40	15	5	3	23	**85**
30		43	16	5	3	25	**92**
31		28	10	4	2	16	**60**
32		48	17	6	3	28	**102**
33	8	47	17	6	3	27	**99**
34		36	13	5	2	21	**76**
35		47	17	6	3	27	**99**

36		56	20	7	4	32	**119**
37	9	44	16	6	3	25	**93**
38		53	20	7	3	31	**114**
39		56	20	7	4	32	**119**
40		46	17	6	3	27	**99**
41	10	52	19	7	3	30	**110**
42		43	16	5	3	25	**91**
43		55	20	7	4	32	**118**
44		56	21	7	4	33	**120**
45	11	44	16	5	3	25	**93**
46		62	23	8	4	36	**132**
47		53	19	7	3	31	**113**
48		55	20	7	4	32	**118**
49	12	46	17	6	3	27	**98**
50		34	13	4	2	20	**73**
51		57	21	7	4	33	**122**
52		78	28	10	5	45	**166**
53	13	56	21	7	4	33	**120**
54		55	20	7	4	32	**118**
55		51	19	6	3	29	**108**
56		62	23	8	4	36	**132**
57	14	48	18	6	3	28	**104**
58		53	19	7	3	31	**112**
59		53	20	7	3	31	**114**
60		60	22	8	4	35	**128**
61	15	59	22	7	4	35	**127**
62		50	18	6	3	29	**108**
63		54	20	7	3	31	**115**
64		58	21	7	4	33	**123**
65	16	55	20	7	4	32	**118**
66		51	19	6	3	30	**110**
67		45	16	6	3	26	**95**
68		50	18	6	3	29	**107**
69	17	38	14	5	2	22	**81**
70		45	17	6	3	26	**97**
71		61	22	8	4	35	**129**
72		50	18	6	3	29	**107**
73	18	49	18	6	3	28	**104**
74		51	19	6	3	30	**110**

75		59	21	7	4	34	**125**
76		34	13	4	2	20	**73**
77	19	33	12	4	2	19	**71**
78		50	18	6	3	29	**107**
79		42	15	5	3	25	**90**
80		42	15	5	3	25	**90**
81	20	40	15	5	3	23	**85**
82		40	15	5	3	23	**85**
83		31	11	4	2	18	**67**
84		27	10	3	2	16	**58**
85	21	36	13	5	2	21	**78**
86		47	17	6	3	27	**101**
87		42	16	5	3	25	**91**
88		33	12	4	2	19	**70**
89	22	32	12	4	2	19	**69**
90		35	13	4	2	20	**74**
91		26	9	3	2	15	**55**
92		30	11	4	2	17	**64**
93	23	21	8	3	1	12	**44**
94		25	9	3	2	15	**54**
95		24	9	3	2	14	**50**
96		28	10	4	2	16	**61**

Table C-9 Total Passenger Vehicle Volume – 15-minute Intervals

Matrix	**Hour**	**Ambassador Bridge**	**Blue Water Bridge**	**Total Cars**
1	0	22	14	**35**
2		32	21	**53**
3		32	21	**53**
4		54	35	**89**
5	1	73	16	**88**
6		24	5	**29**
7		49	10	**59**
8		0	0	**0**
9	2	24	13	**37**
10		0	0	**0**
11		24	13	**37**
12		57	30	**86**
13	3	17	2	**20**
14		24	3	**28**
15		21	3	**24**
16		14	2	**16**
17	4	12	3	**15**
18		16	4	**20**
19		20	5	**25**
20		25	6	**31**
21	5	38	12	**50**
22		53	17	**70**
23		41	14	**55**
24		43	14	**57**
25	6	121	31	**153**
26		111	29	**139**
27		113	29	**143**
28		127	33	**160**
29	7	200	44	**244**
30		194	43	**237**
31		166	37	**203**
32		150	33	**183**
33	8	102	36	**138**
34		131	46	**177**
35		119	42	**161**
36		159	56	**215**

37	9	87	51	**137**
38		94	56	**150**
39		79	46	**125**
40		75	44	**119**
41	10	59	50	**109**
42		85	73	**158**
43		47	40	**87**
44		88	75	**163**
45	11	58	55	**113**
46		53	50	**103**
47		40	37	**77**
48		114	107	**221**
49	12	47	41	**88**
50		104	90	**194**
51		60	52	**112**
52		72	63	**135**
53	13	94	90	**184**
54		45	44	**89**
55		91	87	**178**
56		65	62	**127**
57	14	97	80	**177**
58		73	60	**132**
59		79	66	**145**
60		90	74	**164**
61	15	83	77	**159**
62		57	53	**110**
63		99	91	**190**
64		89	82	**172**
65	16	82	67	**149**
66		94	78	**172**
67		60	49	**109**
68		82	67	**149**
69	17	60	47	**107**
70		92	72	**164**
71		78	61	**139**
72		71	56	**126**
73	18	86	73	**159**
74		72	61	**132**
75		72	61	**132**

76		68	58	**126**
77	19	51	40	**91**
78		65	51	**117**
79		62	48	**110**
80		62	48	**110**
81	20	47	31	**78**
82		63	41	**104**
83		52	34	**87**
84		52	34	**87**
85	21	63	64	**126**
86		26	27	**53**
87		52	53	**105**
88		52	53	**105**
89	22	112	59	**171**
90		28	15	**43**
91		35	18	**53**
92		49	26	**75**
93	23	44	17	**61**
94		44	17	**61**
95		44	17	**61**
96		44	17	**61**

Table C-10 Volume Breakdown for each Destination – Passenger Vehicles

Matrix	**Hour**	**17%**	**33%**	**17%**	**17%**	**17%**	**Total**
		Toledo	**Chicago**	**Lansing**	**Flint**	**Sterling Heights**	
1	0	6	12	6	6	6	**36**
2		9	18	9	9	9	**54**
3		9	18	9	9	9	**54**
4		15	30	15	15	15	**90**
5	1	15	29	15	15	15	**89**
6		5	10	5	5	5	**29**
7		10	20	10	10	10	**60**
8		0	0	0	0	0	**0**
9	2	6	12	6	6	6	**38**
10		0	0	0	0	0	**0**
11		6	12	6	6	6	**38**
12		14	29	14	14	14	**86**
13	3	3	7	3	3	3	**20**
14		5	9	5	5	5	**28**
15		4	8	4	4	4	**24**
16		3	5	3	3	3	**16**
17	4	2	5	2	2	2	**15**
18		3	7	3	3	3	**20**
19		4	8	4	4	4	**25**
20		5	10	5	5	5	**31**
21	5	8	17	8	8	8	**50**
22		12	23	12	12	12	**70**
23		9	18	9	9	9	**55**
24		9	19	9	9	9	**57**
25	6	25	51	25	25	25	**153**
26		23	46	23	23	23	**139**
27		24	48	24	24	24	**143**
28		27	53	27	27	27	**160**
29	7	41	81	41	41	41	**244**
30		40	79	40	40	40	**237**
31		34	68	34	34	34	**203**
32		30	61	30	30	30	**183**
33	8	23	46	23	23	23	**138**
34		29	59	29	29	29	**177**
35		27	54	27	27	27	**161**

36		36	72	36	36	36	**215**
37	9	23	46	23	23	23	**137**
38		25	50	25	25	25	**150**
39		21	42	21	21	21	**125**
40		20	40	20	20	20	**119**
41	10	18	36	18	18	18	**109**
42		26	53	26	26	26	**158**
43		15	29	15	15	15	**87**
44		27	54	27	27	27	**163**
45	11	19	38	19	19	19	**113**
46		17	34	17	17	17	**103**
47		13	26	13	13	13	**77**
48		37	74	37	37	37	**221**
49	12	15	29	15	15	15	**88**
50		32	65	32	32	32	**194**
51		19	37	19	19	19	**112**
52		23	45	23	23	23	**135**
53	13	31	61	31	31	31	**184**
54		15	30	15	15	15	**89**
55		30	59	30	30	30	**178**
56		21	42	21	21	21	**127**
57	14	29	59	29	29	29	**177**
58		22	44	22	22	22	**132**
59		24	48	24	24	24	**145**
60		27	55	27	27	27	**164**
61	15	27	53	27	27	27	**159**
62		18	37	18	18	18	**110**
63		32	63	32	32	32	**190**
64		29	57	29	29	29	**172**
65	16	25	50	25	25	25	**149**
66		29	57	29	29	29	**172**
67		18	36	18	18	18	**109**
68		25	50	25	25	25	**149**
69	17	18	36	18	18	18	**107**
70		27	55	27	27	27	**164**
71		23	46	23	23	23	**139**
72		21	42	21	21	21	**126**
73	18	26	53	26	26	26	**159**
74		22	44	22	22	22	**132**

75		22	44	22	22	22	**132**
76		21	42	21	21	21	**126**
77	19	15	30	15	15	15	**91**
78		19	39	19	19	19	**117**
79		18	37	18	18	18	**110**
80		18	37	18	18	18	**110**
81	20	13	26	13	13	13	**78**
82		17	35	17	17	17	**104**
83		14	29	14	14	14	**87**
84		14	29	14	14	14	**87**
85	21	21	42	21	21	21	**126**
86		9	18	9	9	9	**53**
87		18	35	18	18	18	**105**
88		18	35	18	18	18	**105**
89	22	28	57	28	28	28	**171**
90		7	14	7	7	7	**43**
91		9	18	9	9	9	**53**
92		12	25	12	12	12	**75**
93	23	10	20	10	10	10	**61**
94		10	20	10	10	10	**61**
95		10	20	10	10	10	**61**
96		10	20	10	10	10	**61**

Table C-11 Final O-D Matrix for Trucks

	Toronto	**Toledo**	**Chicago**	**Lansing**	**Flint**	**Sterling Heights**	**College EB**	**College WB**	**Tecumseh Rd WB**	**Tecumseh Rd EB**	**Prince Rd**	**Totten St**	**Malden Rd WB**	**EC ROW EB**	**EC ROW WB**	**Essex**
Toronto	0	3773	1380	475	241	2195										
Toledo		0														
Chicago			0													
Lansing				0												
Flint					0											
Sterling Heights						0										
College EB							0									
College WB								0								
Tecumseh Rd WB									0							
Tecumseh Rd EB										0						
Prince Rd											0					
Totten St												0				
Malden Rd WB													0			
EC ROW EB														0		
EC ROW WB															0	
Essex																0

Table C-12 Final O-D Matrix for Passenger Vehicles

	Toronto	**Toledo**	**Chicago**	**Lansing**	**Flint**	**Sterling Heights**	**College EB**	**College WB**	**Tecumseh Rd WB**	**Tecumseh Rd EB**	**Prince Rd**	**Totten St**	**Malden Rd WB**	**EC ROW EB**	**EC ROW WB**	**Essex**
Toronto	0	1746	3492	1746	1746	1746								742	580	
Toledo		0														
Chicago			0													
Lansing				0												
Flint					0											
Sterling Heights						0										
College EB							0									
College WB								0								
Tecumseh Rd WB									0							
Tecumseh Rd EB							197	197		0						
Prince Rd											0					
Totten St												0				
Malden Rd WB							1194	1194			244	244	0			
EC ROW EB														0		
EC ROW WB											696	696			0	
Essex														3920		0

APPENDIX D: Demo Network Screenshots

This appendix presents the screenshots from the demo network simulation with and without the presence of connected vehicles.

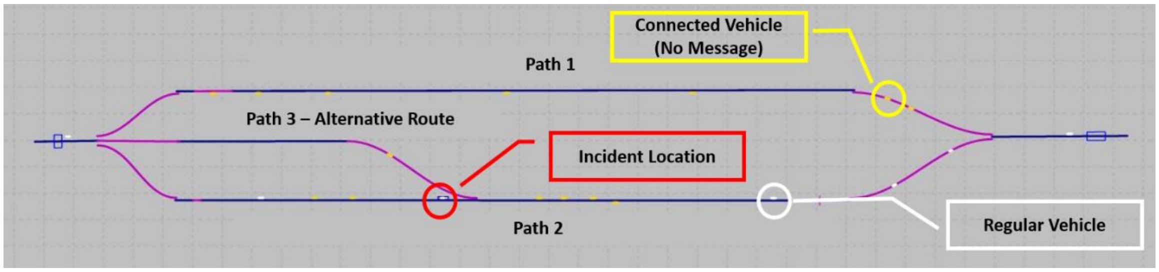

Figure D-1 Demo Network - No V2V Scenario

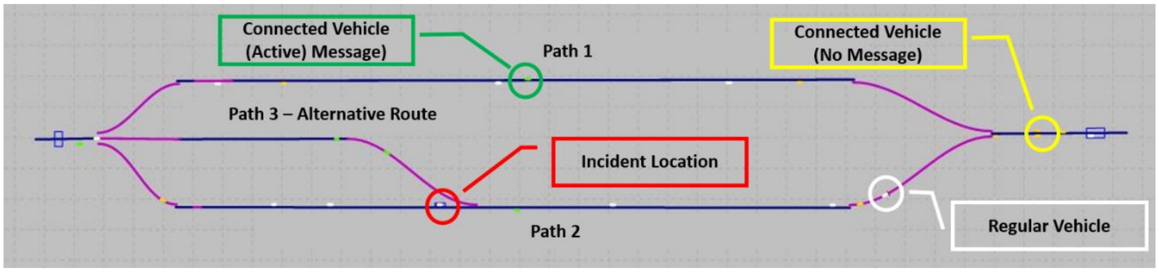

Figure D-2 Demo Network - V2V Scenario

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