Economic Criticality of Ontario's Highway Infrastructure

by

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Author's declaration

I hereby declare that I am the sole author of this thesis. This is a true copy of the thesis, including any required final revisions, as accepted by my examiners.

I understand that my thesis may be made electronically available to the public.

Abstract

Ontario is the economic center of Canada and hence generates a significant amount of freight activity. Moving forward, population growth coupled with growing and diverse trade strategies are likely to place new and increased demands on Ontario's aging infrastructure. Since Ontario shippers and carriers rely on the mobility and accessibility provided by transportation systems, any restrictions or disruptions can have detrimental outcomes not only for the Province's economy but also for the economy of Canada as a whole. Events that disable parts of the highway transportation network, ranging from weather conditions to construction closures, may affect freight travel times and ultimately threaten economic productivity. While previous studies of criticality typically focus on the impacts of natural disasters or terrorist attacks on system-wide travel times, they have not quantified the costs associated with disruptions to the economy via the freight transportation system.

This research quantifies the economic criticality of highway infrastructure in Ontario, Canada, using a new measure of criticality that determines the cost of highway closures in dollar values ($) based on the value of goods, the time delayed, and the associated value of time. Measured this way, criticality is correlated with truck volumes, but differs by considering the values of shipments and network redundancy, resulting in new insights to critical freight infrastructure. For example, due to the high redundancy of the highway network within the Greater Toronto Area (GTA), highways become more critical further away. Moreover, sections of Highway 401 located west of the GTA are found to be more critical than those located east of the GTA because of lower redundancy in the western portion of the network, despite carrying lower truck volumes. Finally, with the cost of these disruptions quantified in dollars, one can then calculate the monetary benefits of potential transportation improvements for comparison (i.e., cost-benefit analysis).

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Dedication

I would like to dedicate my thesis to my beloved parents and lovely husband for their endless love, patience, kindness and support.

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1. Introduction

1.1. Background

Ontario is the economic heartland of Canada and hence generates a significant amount of goods movement. It is estimated that Ontario's multimodal transportation system moves over $1.3 trillion in goods per year (Perttula, 2012). Ontario's multi-modal system carries 49% of Canada's total international trade (Perttula, 2012). Trade aside, southern Ontario is a national hub for production, consumption, and transshipment of goods. Moving forward, population growth coupled with growing and diverse trade strategies (e.g., Comprehensive Economic and Trade Agreement) are likely to place new and increased demands on Ontario's aging infrastructure.

Efficient and reliable freight transportation is critical to a country's economic prosperity and competitive advantage. Producers use transportation systems to move raw materials into processing facilities, intermediate goods to factories, and finished goods from factories to distribution centers, stores, and export countries. In terms of both tonnage and value, trucking is a common mode of transportation in North America. For example, trucks transported 68% of the Province of Ontario's export value and 84% of the province's import value in 2006 (Metrolinkx, 2016). In a developed economy where many goods are expensive and needed in tightly scheduled manufacturing and distribution systems (e.g. Just In Time), shippers and carriers require a reliable transportation system. Late arrivals could have significant costs for factories waiting for parts to assemble, groceries that are lost to spoilage, and for carriers who miss guaranteed delivery times. Hence, events that disable parts of the highway transportation network, ranging from weather conditions to construction closures, may affect freight travel times and ultimately threaten economic productivity. Parts of the network that have particularly severe economic impacts may be considered critical.

1.2. Problem statement

Identifying critical network elements is important for designing and maintaining transportation systems. While previous studies of criticality (e.g., using Volume, Volume/Capacity, and Network Robustness Index) typically focus on the impacts of natural disasters or terrorist attacks on system-wide travel times, they have not quantified the costs associated with disruptions to the economy via the freight transportation system. The underlying assumption of previous approaches is either that: all traffic flows are homogenous; or the value of time for every road user is equal. However, traffic flows are not homogenous and road users have different values of time. For example, a road user carrying high-value commodities or just-in-time goods has a higher value of time than does a road user making a discretionary trip (e.g., shopping). Therefore, a closed link that causes longer delays or delays to a higher value of goods is more economically critical than a closed link that causes shorter delays or delays to a lower value of goods.

1.3. Research objectives

The central aim of this research is to study the economic criticality of Ontario's highway infrastructure (i.e., those roads where disruptions would have particularly severe economic consequences). Individual research objectives are as follows:

1. Conduct a literature review on existing criticality measures to identify previous methodological approaches and compare their purposes and limitations.
2. Propose a new measure of criticality, which measures the system-wide short-term economic impacts to freight shippers from the disruption or closing of a link, and demonstrate the theoretical differences between this measure and the key approaches identified in the literature review (Objective 1).
3. Develop an inter-regional travel demand model of Ontario's highway network to implement the proposed measure (Objective 2). In this regard, four-step modelling is used, including: trip generation, trip distribution, mode split, and traffic assignment
4. Compare the various criticality measured identified through literature review (Objective 1) with the proposed method (Objective 2) on the newly developed Ontario travel demand

model (Objective 3), and note major findings, differences, limitations, and recommended applications.

1.4. Research methodology

This project was completed based on the most recent available data and the area of study is the province of Ontario in Canada. In this research, two methodologies have been used: one for determining the criticality and the other to model traffic flows. Trade criticality is introduced as a new method to find the criticality of transportation links. Criticality is measured by removing or closing a link and measuring the cost of delays ($) associated with all freight shipments in the network. The equations and descriptions are explained in section 3.1 in detail.

The four-step model, which is the second methodology used in this research, is a traditional paradigm to model the number of trips in the transportation system. This model includes four stages: trip generation, trip distribution, mode split and traffic assignment. This research considers all trips - work, discretionary and others. To conduct trip generation, linear regression is used. For trip distribution, a gravity model is estimated and balanced with bi-proportional updating. Mode splits are based on travel statistics (since studying mode shifts is not the focus of this study). The traffic assignment takes the form of a User Equilibrium (UE) traffic assignment using the SOLA (Second-Order Linear Approximation) algorithm in the EMME 4 software.

1.5. Structure of thesis

This chapter introduces the background, motivation, research problem, and objectives and scope of the work. The remainder of this thesis is organized as follows:

The next section reviews previous literature focused on transportation network criticality, and identifies gaps in determining critical links from an economic, trade, and/or freight perspective.

Chapter 3, the methods section, introduces a new measure of criticality, specifically aimed at capturing costly disruptions to the freight transportation system, and includes a theoretical example of how this measure differs from earlier approaches. This chapter also explains the four-step modelling (FSM) paradigm used in this research to develop a new inter-regional travel demand model of Ontario. FSM includes trip generation, trip distribution, mode split, and traffic assignment.

The data used to develop the Ontario travel demand model are described in Chapter 4, which includes data for determining passenger and freight demands. In particular, the Transportation Tomorrow Survey (TTS) ("Data Management Group – Introduction," n.d.) and the Ministry of Transportation of Ontario (MTO) Commercial Vehicle Survey (CVS) were primarily used for passenger and freight demands, respectively. The first part of Chapter 4 describes the available TTS data along with other supporting data needed to model passenger demands between the Census Divisions (CDs) of Ontario. In second part of Chapter 4, freight demands, including total truck trips, cargo-carrying truck trips, empty truck trips, and cargo values, are determined directly from the MTO CVS.

Chapter 5 describes the results of developing an Ontario travel demand model. The linear regression models for trip production and trip attraction are presented, including tables summarizing the model estimates for the 14 CDs for which complete data is available, as well as the results of applying the model to estimate trip production and attraction for the remaining CDs. Trip distribution results are also presented from the linear regression results of a gravity model, and comparisons are shown for trip production and trip attraction between trip generation and trip distribution, before and after balancing. The chapter continues with a description of model validation and calibration. Final correlation coefficients for travel times, and truck and passenger car volume, for all, other, and specific highways (401, 407 and QEW) for the AM and PM peak periods are presented.

In Chapter 6, the proposed and previous criticality measures are implemented in the Ontario model. In total, three measures are compared: 1) truck volumes; 2) Network Robustness Index (NRI); and 3) the proposed measure, "trade criticality". Afterwards, results are discussed in the context of freight transportation planning in Ontario, and recommendations are made where the proposed measure may be most useful.

Finally, Chapter 7 outlines conclusions and limitations of the proposed approach before providing a brief agenda for future research.

2. Literature Review

In this section, the literature review of determining the criticality of roads is discussed. In the first part, some of the various terminology of criticality is explained, and in the second part, previous criticality studies are described.

2.1. Terminology

Prior to discussing previous literature, it is worthwhile to note some of the various terminology (italicized throughout this section) that is often used to describe essentially the same phenomena. Jenelius et al. (2006) suggest using the term vulnerability, which can be divided into two parts, one containing the probability of a hazardous event, and the other containing the consequences, which they call exposure. Hence, $Vulnerability = Probability\ \times Exposure$. Moreover, they define criticality similarly to vulnerability, where weakness and importance are used instead of probability and exposure, respectively (i.e.,$Criticality = Weakness\ \times Importance$.). These terms are akin to the typical formulation of risk (i.e., $Risk = Probability\ \times Consequence$). Snelder et al. (2008) suggest robustness and vulnerability have a strong relation, but they are each other's opposites: vulnerability describes the weakness of a network and robustness describes the strength of a network.

Cox et al. (2011) and Maoh et al. (2011) have begun using the term resiliency to describe essentially the same concepts as vulnerability and criticality. A common theme in the analysis and evaluation of network-based critical infrastructure is *interdiction* - where network elements (nodes or arcs) are disabled in a model, disrupting flow through the network (Murray, Matisziw, & Grubesic, 2007).

2.2. Previous studies of criticality

2.2.1. Consequences of failure in links

Jenelius et al. (2006) used the increase in generalized travel cost to measure the consequences of failure in links. Two points of views are used to reflect the increase in travel cost: "equal opportunities" and "social efficiency". All roads are considered to be equal and to have equal opportunities, but from the social efficiency perspective, the roads that are used more, are assumed to be more important. They noted political judgement could use to decide which of these two perspectives to use in a certain situation. Jenelius et al. (2006) proposed two measures for the importance of a link: 1) the system-wide increase in travel time as a result of the link being disrupted or closed; and 2) the amount of unsatisfied demand as a result of any disconnected parts in a network. Jenelius et al. (2006) also stated that vulnerability should be considered in all road-project assessments because vulnerability causes difficulty and additional costs for users.

Taylor and D'Este (2007) determined the socio-economic impacts of network deterioration for the vulnerability analysis of transport networks in their analysis. They stated that consequences and risks related to failures at different places should be considered, as well as their probabilities. Taylor and D'Este (2007) suggested studying network reliability before investigating network vulnerability. In network reliability studies, not only are urban areas significant, but also regional coverage and inter-urban connectivity. Two supplementary forms of reliability are described by them: travel time reliability and capacity reliability. These two concepts require further research before practical application. Ultimately, network connectivity, travel time reliability, and capacity connectivity all contribute to network reliability. They suggested more detailed analyses are needed, investigating vulnerability in both rural and urban areas, and the goal of transport engineers is to decrease vulnerabilities

Taylor and D'Este (2007) stated that in network vulnerability studies, only the consequences are investigated and the probability of failure is not considered. They also identified the differences between network reliability and network vulnerability: network reliability focuses on connectivity and probability, whereas vulnerability concentrates on network weakness and failure consequences. Based on their research, the risk is the combination of probability and consequence, and its evaluation procedure is as follows: set up the background, recognize the dangers, study the risks, and evaluate these risks.

2.2.2. Volume over capacity (V/C)

Scott et al. (2006) introduced a new approach for determining network criticality. Before their research, critical links were often identified by the Volume over Capacity (V/C) ratio. In their research, critical links are evaluated by closing links; after that, the impacts of those road closures on the entire transport network are assessed, and then the results are compared with when the links were not removed. To identify the critical links, Scott et al. (2006) considered network connectivity in addition to the traffic flows and capacity of the network, because network connectivity has an impact on reliability as well as on performance reliability.

2.2.3. Network Robustness Index (NRI)

Scott et al. (2006) called their measure the: Network Robustness Index (NRI). Two main parameters are considered for evaluating it: first, travel time (t_a), which derives from the link performance function or volume-delay function for link a, and second, traffic flow (x_a), which is the volume of traffic for link a. The NRI (q_a) is calculated by the equation 1:

$$q_a = c_a - c \tag{1}$$

where

$$c_a = \sum_a t_a x_a \delta_a \tag{2}$$

$$\delta_a = \begin{cases} 1 & \text{if link a is not a removed link} \\ 0 & \text{otherwise} \end{cases} \tag{3}$$

and,

$$c = \sum_a t_a x_a \tag{4}$$

Hence, the NRI for a link (a) is the difference in system-wide travel times between the base case (c) and the case with link a removed (c_a).

To explore whether the results obtained from the Network Robustness Index are the same as the results from other measures like V/C ratio, Scott et al. (2006) considered three networks with the top ten values for the NRI and their relevant value for V/C ratio in a table. They demonstrated that in Network 1, there is no similarity between results, and in Networks 2 and 3, only 3 and 6 links have the same results in both methods, respectively. This comparison illustrates the fact that ignoring the system-wide travel time results in different results in most cases.

Snelder et al. (2008) stated that increasing demands causes the growth in total travel time to become more than linear and the effect of incidents increases. Therefore, making the roads more robust is necessary for the road network over the long-run.

2.2.4. Terrorist attacks

Cox et al. (2011) indicated that terrorists often target transportation systems because transport networks are highly sensitive to changes, which results in extensive detriment to the economy. They believed that measuring the resiliency is necessary to make a decision and plan for the security of the countries. In their work, only passenger trips is considered as a mode and the basic form of transportation system as a case study is investigated.

Maoh et al. (2011) also used the term resiliency to explain the vulnerability and criticality of the road network in Ontario, Canada. They mentioned that there are three categories of strategy to decrease terrorist attack effects: hardening, response, and resilience. With hardening, it is possible to make a network more robust physically. Response means ensuring that first responders can quickly move to sites so as to deal with destruction right after an event. The ability of a system to stay operable or to return to operability soon after an event, termed resilience. Response is concerned with organizing action plans, but hardening and resilience are related to critical infrastructure.

2.2.5. Natural disasters

2.2.5.1. Flood

Sohn (2006) proposed an accessibility index which combines the distance-decay effect and traffic volume impact on the transportation network. Sohn (2006) also compared two cases: 1) when the increases in travel costs from a link being disrupted or closed are measured in distance only; and 2) when these increases in travel costs measured in distance are weighed by traffic. These two cases indicate different results. In the second case, the percentage loss of accessibility increases when a link is disrupted. Some links stay prominent in both cases, for example when that link provides the only route in and out of a specific county. Retrofit (a pre-disaster measure) and restoration (a post-disaster measure) are two measures used to limit natural disaster effects but due to budget constraints, they cannot be retrofitted on all links completely. The distance-only measure results better for counties which do not have other alternative backup routes, whereas the distance-traffic volume measure greatly restricts accessibility due to the disruption of links with high traffic volume. Local political and geographic situations tend to determine which criteria will be selected for a project. Note that Shon's (2006) second measure is the same as the one used by Jenelius et al. (2010), Taylor and D'Este (2007), and Scott et al. (2006).

Jenelius (2010) focused on the inequity implications of link closures and suggested that researchers additionally use the coefficient of variation (CV) to measure how unevenly travel time increases will be distributed among travelers (equity importance) and how the total travel time (efficiency importance) will rise. The roads which are closed for a few days and the roads which are outside the most congested metropolitan zones are considered in his research. The significance measures rely on the growth in travel time when the roads are closed. Jenelius (2010) showed that the relationship between equity importance and efficiency importance is inverse.

Jenelius (2010) assumed that when a link is closed, users decide to change their routes or delay their trips until that link opens again. In the real world, some travelers prefer to alter their mode of transport to other available modes or tend to change their destination if it is possible. Sometimes, they simply cancel their trips. In fact, travelers usually compare the costs of delaying and canceling trips and then choose the one with lower costs. In many criticality studies, these complications are ignored, and it is assumed the network re-converges to a new user equilibrium (UE).

2.2.5.2. Earthquake

Giuliano et al. (1998) considered the Northridge earthquake impacts on travel behavior. They investigated two transportation roads, which are greatly disrupted, to find the changes of travel pattern during the rebuilding time. They determined the role of public transit and commuters' behavioral responses, instead of focusing on impact to passenger demands in urgent situations, and evaluate the cost of transit in those conditions. From their observations, they concluded that fast rebuilding of a damaged transportation system will not be possible unless travelers adapt to the use of temporary routes or vehicles and are provided with more transportation options (e.g., public transit supply).

Ham et al. (2005) evaluated the economic impacts of unanticipated incidents like an earthquake, by using an intra zonal commodity flows model, that combines zonal input-output communications, and applying a correlated transportation system. Recuperation and rebuilding activities, plus the original loss and harm cause the economic impacts. Two economic impacts in particular, must be evaluated in recovering and rebuilding facilities: direct and indirect. Direct, that is the immediate economic impacts that occur when production and commerce are interrupted by an event, and indirect, which occur later as the interruption's influence become widespread.

Generally, studies of transportation vulnerability, criticality, robustness, resiliency, and so on, typically focus on the impacts of natural disasters or terrorist attacks on system-wide total travel times (Cox et al., 2011; Giuliano & Golob, 1998; Ham et al., 2005; Jenelius et al., 2006; Murray et al., 2007; Sohn, 2006; Srinivasan, 2002; Taylor & D'Este, 2007). For example, the earliest study (Giuliano & Golob, 1998) focused on the impacts of an earthquake on highway and transit use, prior to which research on travel behavior responses to major disasters was virtually nonexistent. It is not surprising that one of the earliest papers proposing a quantitative metric for network vulnerability occurred shortly after September 11th, 2001 (Srinivasan, 2002). Many of the studies above were also motivated by natural disasters or terrorist attacks: Ham et al. (2005) was interested in hypothetical earthquake scenarios in the Midwest United States; Sohn (2006) was motivated by potential flood damage in Maryland; Jenelius et al. (2006) cited security risks including terrorist attacks; Murray et al. (2007) also cited terrorism and security threats as motivation; Cox et al. (2011) acknowledge that while resiliency is traditionally explored in the context of natural disasters, it is important in the "terrorist realm" as well; and Taylor and D'Este (2007) cited perceptions of risks and threats to infrastructure from both natural disasters and terrorist attacks in their list of motivations for accessing the vulnerability of the Australian road network.

2.2.6. Four-step model

A traditional way to estimate the number of people or vehicles using the transportation system is the four-step model (FSM). The FSM includes 4 analyses: trip generation, trip distribution, mode split, and traffic assignment. After using a specific methodology for each step, its output will be used for the next sequential step (Sheffi, 1984).

2.2.6.1. Trip generation

The first step is trip generation, which measures the number of trip produced and attracted at either the household or zonal levels. The number of trip produced or trip attracted for each trip purpose of interest will be determined in trip generation step.(Lipping Fu, 2016)

2.2.6.2. Trip distribution

The second stage of the four step travel demand model is trip distribution, in which the number of generated trips (produced or attracted) are distributed to corresponding zones. (Lipping Fu, 2016)

2.2.6.3. Mode split

The third stage of FSM is mode split or mode choice. In the mode choice step, the modes of trips between origin i and destination j (T_{ij}) are determined; for example some trips will take transit, some of them by personal vehicle and others by carpooling. Random Utility Maximization (RUM) based models are most commonly used for mode choice modelling.(Lipping Fu, 2016)

2.2.6.4. Traffic assignment

Traffic assignment is the fourth step of Four-Step Model (FSM) and it can be done by two approaches: user equilibrium assignment (UE) and system optimal assignment (SO). UE is based on the first principle of Wardrop's assumption and SO is based on the second principle. (Lipping Fu, 2016)

2.2.6.4.1. User equilibrium assignment (UE)

In the first approach of traffic assignment, UE, it is assumed that each driver determines his/her travel time (cost) and tries to minimize that. Road users act selfishly and don't care about the total system travel time (Lipping Fu, 2016).

2.2.6.4.2. System optimal assignment (SO)

In the second approach of traffic assignment, SO, it is assumed that drivers are aware of the effects of their route choice on total travel time. In SO approach, all drivers attempt to minimize the aggregate travel time (cost) by choosing the appropriate route (Lipping Fu, 2016).

2.3. Research gap

First, many previous studies of transportation economic criticality focus narrowly on criticality from the perspective of natural disasters or terrorist attacks. However, identifying critical transportation network elements is important for regular operation of the transportation system and the economy. An analysis of Most Critical Links (MCLs) is useful for many applications within these domains. For example, physical redundancy can be planned for the MCLs to reduce overall economic vulnerability. Design efforts can be focused towards reducing the likelihood and consequence of disruptions or closures on these links. Maintenance and reconstruction efforts can be coordinated to avoid scenarios involving combinations of links that create the greatest increase in economic impacts. Prioritization for road maintenance and repair should also consider economic criticality. MCLs could also be considered for greater surveillance through more highway patrols by policing organizations. These examples demonstrate the many practical applications of knowing the economic criticality of transportation infrastructure.

Second, previous measures of criticality do not capture the costs associated with disruptions to the economy via the freight transportation system. For example, shippers and carriers may assign a value to increases in travel time, ranging from $25 to almost $200 per hour, depending on the commodity carried (Sedor & Caldwell, 2002). In that sense, a closed link that causes longer delays or delays to higher-value goods is more economically critical than a closed link that causes shorter delays or delays to lower-value goods. By measuring the volume-weighted increases in network travel times, previous studies implicitly assume all vehicles in the network have the same value of time. This assumption is questionable for passenger trips, since work-trips may have a higher value of time than discretionary travel such as shopping trips. In the case of truck trips, this assumption is invalid since the freight carried by trucks plays a central role in determining the associated values of time.

Hence, this research focuses on determining the economic criticality of Ontario's highway infrastructure (i.e., those roads where disruptions would have particularly severe economic consequences), for the purpose of freight transportation planning, operations, and maintenance.

3. Methodology

In this chapter, the methodologies used in this research are presented: criticality measurement and four-step modelling. In the first part, criticality, a summary of previous measures are explained and then trade criticality is introduced as a new measure. In the second part, describing four-step modelling, the stages of the traditional model to simulate trips are described.

3.1. Criticality

Criticality has commonly been measured by one of the three following methods: Volume, Volume/Capacity, and the Network Robustness Index. Volume and Volume/Capacity can be obtained easily if the data for demand (e.g., traffic counts) and supply (e.g., geometric information) of roadways are available. On the other hand, the Network Robustness Index (NRI), introduced by Scott et al. (2006) as explained in detail in chapter 2, requires a travel-demand model to simulate link closures.

In this research, trade criticality is introduced as a new method to find the criticality of transportation links. Criticality is measured by removing or closing a link and measuring the cost of delays ($) associated with all freight shipments in the network. For a single shipment *(i)*, the cost of delay *(q_i)* is calculated by Equation 5:

$$q_i = d_i \times t_i \times \alpha \tag{5}$$

where

d_i is the dollar value ($) of shipment i;

t_i is the time delay (minutes) experienced by shipment i (additional time); and

α is the value of time as a percentage of the shipment value (% per minute).

Equation 5 represents a short-term measure of economic criticality, since it captures the immediate costs of shipment delays, all else being equal. In the long-run, all else is not equal, since major changes to the highway network will influence long-run decisions such as firm location choices. In this light, Equation 5 can be used to determine the “short-term economic criticality”, or “trade criticality", of transportation networks. For the remainder of this thesis, this measure is referred to as trade criticality.

The values of shipments (d_i) depend on the commodities shipped, while the values of delays (t_i) depend on the properties of the transportation network. The value of time (α) is a parameter that must be estimated exogenously or taken from the literature. For example, Hummels and Schaur (Hummels, D. L., 2012) estimate that each day in transit is worth 0.6 to 2.1 percent of the value of the shipment. Note that the absolute value of this parameter is not important when making comparisons of trade criticality between highway segments in the network since it scales all shipment values by the same percentage (Equation 5).

Figure 3-1 shows a hypothetical network model to illustrate the unique property of the proposed measure. The network shows truck volumes (V), capacities (C), and dollar value of shipments (D) on Link 1 and 2 ($D = \sum_i d_i$). Volumes (V) represent the observed flow of trucks (veh/hour), capacity (C) represents the maximum allowable flow of vehicles (veh/hour), and the dollar value of shipments (D) represents the actual flow of dollars ($/hour) carried by the trucks. Without loss of generality, assume the volume-delay curves (or link-performance functions) of Links 1 and 2 are the same, and that there is a relatively long travel time on Link 3, such that the network as illustrated is in User Equilibrium (UE).

Now consider the criticality of Links 1 and 2 by four measures: (1) volume; (2) volume/capacity (i.e., roadway demand/supply); (3) NRI (i.e., increase in total travel time when the link is closed); and (4) trade criticality (i.e., increase in the cost of shipment delays when the link is closed). By inspection, both truck volume and the volume/capacity ratio suggest Link 2 is more critical than Link 1. That is, 5 trucks are observed on Link 2 compared to only 3 trucks on Link 1, and since their capacities are the same (10 veh/hour), Link 2 has a V/C ratio of 0.5 compared to a V/C ratio of only 0.3 on Link 1. Similarly, the increase in total travel time is highest when Link 2 is closed, since 5 trucks must additionally traverse Link 3, instead of only 3 trucks additionally traversing Link 3 when Link 1 is closed (recall that links 1 and 2 have the same volume-delay curves, so that the travel time on Link 1 when Link 2 is closed, is equal to the travel time on Link 2 when Link 1 is closed). However, the 3 trucks on Link 1 are carrying higher-value goods (averaging $30/truck), whereas the trucks on Link 2 are carrying lower-value goods (averaging $8/truck). Hence, the increase in the cost of shipment delays is highest when Link 1 is closed, since $90 of shipments must additionally traverse Link 3, instead of only $50 of shipments additionally traversing Link 3 when Link 1 is closed. In this example, the first three measures suggest Link 2 is most critical, but the fourth measure identifies Link 1 as most critical by explicitly taking into account the value of shipments.

In any network, these four measures might produce the same or different results, which are functions of the network properties, truck volumes, and shipment values. While all four measures capture an aspect of criticality, only the fourth measure (trade criticality) captures the short-term economic costs associated with disruptions to the freight transportation system.

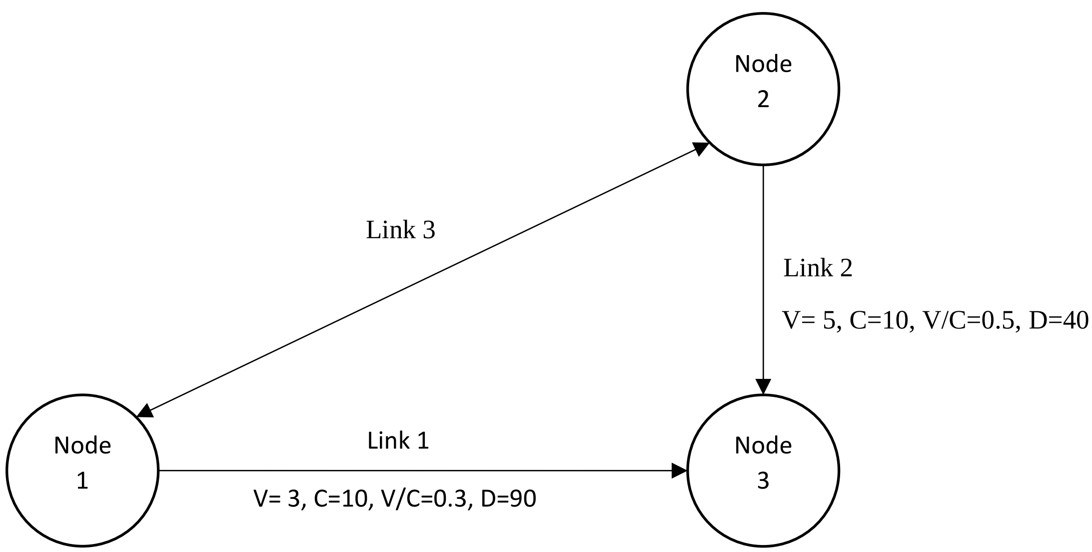

Figure 3-1- Example illustrating trade criticality

Similar to previous approaches (e.g., (Scott et al., 2006)), the trade criticality of each highway segment in a network model can be determined using multiple traffic assignments equal to the number of links in the network. Let v_a, t_a and d_a represent the traffic flow (vehicles/hour), travel time (minutes), and dollar value of goods ($/hour) on link a of the network model, respectively. Each link will have a link performance function such that $t_a = f(v_a)$; that is, travel time is a function of traffic flow. Each link's traffic flow (v_a) will have an associated value of goods (d_a) based on its composition of shipments. For a one hour traffic assignment, the system-wide travel times multiplied by the value of shipments ($·minutes) in the network when all links are present (i.e., the base case) is calculated from a UE assignment as:

$$c_0 = \sum_a t_a d_a \tag{6}$$

Second, system-wide travel times multiplied by value of shipments ($·minutes) for each scenario is calculated from a UE assignment on a modified network model with link *k* removed as:

$$c_k = \sum_a t_a d_a \delta_a, \tag{7}$$

where

$$\delta_a = \begin{cases} 1, & if\ link\ a\ is\ not\ the\ link\ removed\ (k \neq a), \\ 0, & otherwise\ (k = a). \end{cases} \tag{8}$$

Finally, the trade criticality of link k, defined as the increase in the cost of delays to all shipments in the network as a consequence of removing link k, is calculated as:

$$q_k = \alpha(c_k - c_0) \tag{9}$$

where q_k is trade criticality of link *k* measured in dollars ($), and α is the value of time as a percentage of shipment values (% per minute).

3.2. Four-step model

The four-step model (FSM) methodology is used in transportation projects to forecast the future travel demands and model "what if" scenarios. This research estimates a four-step model for Ontario, at the resolution of the 49 Census Divisions (CDs) shown in Figure 3-2- (Agricola Odoi, S Wayne Martin, Pascal Michel, John Holt, Dean Middleton, 2003).

The FSM model includes trip generation, trip distribution, modal split and traffic assignment. Figure 3-3 shows an overview of the model.

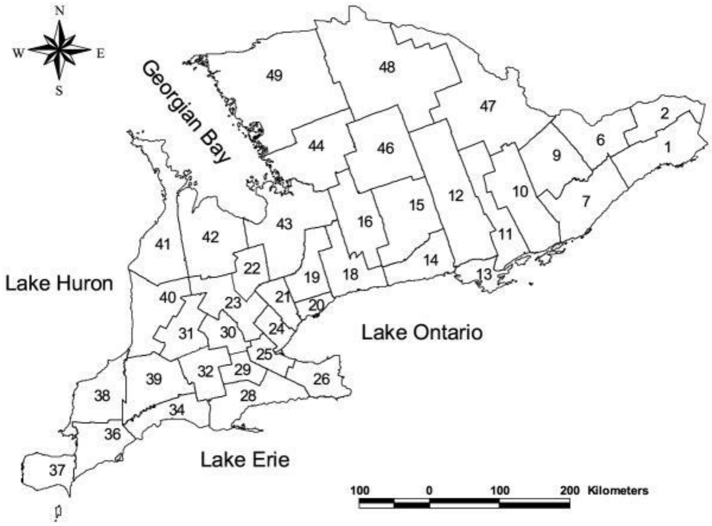

Figure 3-2- Map of distribution of Census Division (CD) of Ontario

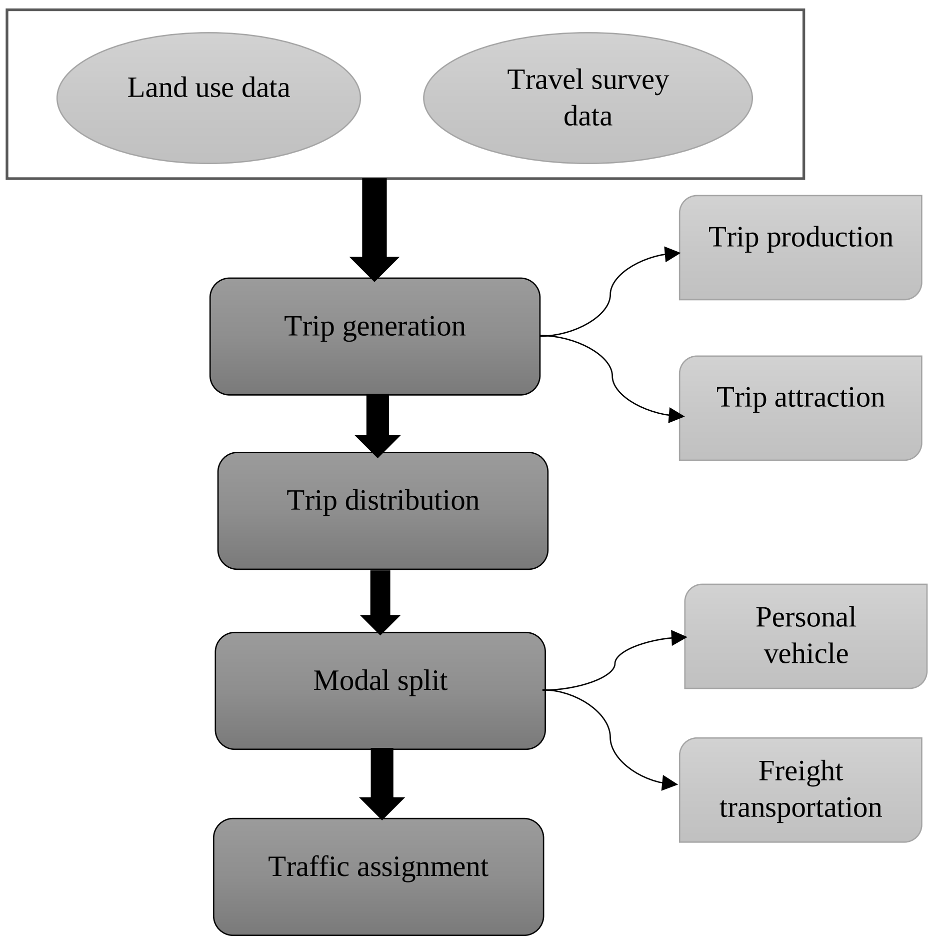

Figure 3-3-Four-step model overview

3.2.1. Trip generation

As shown in flowchart provided in Figure 3-3 the first step is trip generation, which measures the number of trip produced and attracted at either the household or zonal levels. This research considers all trips - work, discretionary and others. Two methods are commonly used to conduct trip generation: cross classification and regression. In this research, linear regression is used. With this approach, it is assumed that the relationship between a dependent variable (*Y*) and independent variables ($X_1, X_2, X_3, ..., X_n$) is linear. The following equation shows a form of a linear model (Lipping Fu, 2016):

$$Y_i = C + X_{i1} + X_{i2} + ... + \mathrm{X}_{in} \tag{10}$$

where:

Y is the number of trip production or attraction by zone i;

$X_{i1}, X_{i2}, ..., X_{in}$ are the main variables influencing trip generation number;

$\alpha_1, \alpha_2, ..., \alpha_n$ are the coefficients obtained from linear regression;

C is a constant given by linear regression analysis.

3.2.2. Trip distribution

The second stage of the four step travel demand model is trip distribution, in which the number of generated trips (produced or attracted) are distributed to corresponding zones. This research uses the gravity model, which is one of the most commonly employed methods for trip distribution. The general equation for doubly constrained gravity model is as follows (Lipping Fu, 2016):

$$T_{ij} = A_i B_j O_i D_j f(C_{ij}) \tag{11}$$

where

T_{ij} is trip between zones i and j;

O_i is trip production from zone i;

D_j is trip attraction of zone j;

$f(C_{ij})$ is the travel deterrence function, which can be inverse function of travel time or generalized travel cost;

A_i and B_j are the so-called row and column balancing factors.

$$\sum_{i=1}^{N} T_{ij} = D_j B_j \sum_{i=1}^{N} A_i O_i f(C_{ij}) \tag{12}$$

$$\sum_{j=1}^{N} T_{ij} = O_i A_i \sum_{j=1}^{N} B_j D_j f(C_{ij}) \tag{13}$$

and since $\sum_{i=1}^{N} T_{ij} = D_j$ and $\sum_{j=1}^{N} T_{ij} = O_i$, the balancing factors $(A_i$ and $B_j)$ are calculated from:

$$B_j = \frac{1}{\sum_{i=1}^{N} A_i O_i f(C_{ij})} \tag{14}$$

$$A_i = \frac{1}{\sum_{j=1}^{N} B_j D_j f(C_{ij})} \tag{15}$$

In this research, a simplified gravity model is used:

$$T_{ij} = K V_i^{\lambda} W_j^{\gamma} e^{(\beta d_{ij})} \tag{16}$$

which can be estimated using a log-linear regression:

$$LnT_{ij} = LnK + \lambda LnV_i + \gamma LnW_j + \beta d_{ij} \tag{17}$$

where:

T_{ij} is the total number of trips flowing between origin *i* and destination *j*; *K* is a constant to be estimated;

V_i is a variable which is related to the origin that representing the ability of generating trips from origin *i* (Number of person's with a driver's license in this study); W_j is the variable which is related to the destination that representing the ability of attracting trips by destination *j* (Number of Employment in this study);

d_{ij} is the distance between origin *i* and destination *j*; and *β, γ, λ* parameters to be estimated.

3.2.2.1. Finding the distances between census divisions (CDs):

Since the network model of Ontario was not yet completed at the time of this research, distances were estimated from google maps data. By using google maps data, the longitude and latitude of 49 CDs of Ontario is determined. Next, Haversine formula is used to find the distances (d_{ij}) (IGIS map, n.d.):

$$hav(\frac{d}{r}) = hav(\phi_2 - \phi_1) + \cos(\phi_1)\cos(\phi_2)hav(\lambda_2 - \lambda_1) \tag{18}$$

where

hav is the Haversine function:

$$hav(\theta) = \sin^2(\frac{\theta}{2}) = \frac{1-\cos(\theta)}{2} \tag{19}$$

and,

d is the distance between zones *i* and *j*;

r is radius of the sphere

ϕ_1, ϕ_2 is latitude of zones *i* and *j* in radians;

λ_1, λ_2 is longitude of zones *i* and *j* in radians.

In this calculation, r = 6360 (km) is assumed, and

ϕ_1, ϕ_2 , λ_1, λ_2 are determined by using google maps data. By manipulating (18), *d* is calculated from equations 20 or 21:

$$d = r\,hav^{-1}(h) = 2r \arcsin(\sqrt{h}) \tag{20}$$

$$d = 2\arcsin\sqrt{\sin^2(\phi_2 - \phi_1) + \cos(\phi_2)\cos(\phi_1)\sin^2(\frac{\lambda_2 - \lambda_1}{2})} \tag{21}$$

3.2.2.2. Matrix balancing:

Since the gravity model is not doubly-constrained, the total trip productions and attractions from the trip generation and trip distribution states will not necessarily be equal. Hence, the trip distribution matrix (T_{ij} matrix) should be balanced. The approach to balancing, often called "bi-proportional updating", "iterative proportional fitting", or the "RAS" method is as follows:

The rows of matrix are balanced in the first step:

Consider the matrix shown in Table 3-1. To balance the rows, a new matrix with T_{ij}* is obtained from equation 22. For example, for *i=1*:

$$T^{*}_{1j} = \left(\frac{T_{1j}}{\sum_{j=1}^{3} T_{1j}}\right) P_{14} \tag{22}$$

Table 3-1- An example matrix for balancing

	1	2	3	4
1	T_{11}	T_{12}	T_{13}	P_{14}
2	T_{21}	T_{22}	T_{23}	P_{24}
3	T_{31}	T_{32}	T_{33}	P_{34}
4	A_{41}	A_{42}	A_{43}	

The columns of matrix are balanced in the second step:

Having the new matrix with balanced rows (step 1), then the columns can be balanced. To balance the columns, the new matrix with T_{ij}** is obtained from equation 23. For example, for *j=1*,

$$T^{**}_{i1} = \left(\frac{T_{i1}}{\sum_{i=1}^{3} T_{i1}}\right) A_{41} \tag{23}$$

By repeating these two steps, the final balanced which satisfies the trip production and attraction totals from the trip generation stage is obtained, while reflecting the distance-decay effect captured by the gravity model.

3.2.3. Mode choice

The third stage of FSM is mode split or mode choice. In the mode choice step, the modes of trips between origin *i* and destination *j* (T_{ij}) are determined; for example some trips will take transit, some of them by personal vehicle and others by carpooling. Random Utility Maximization (RUM) based models are most commonly used for mode choice modelling.

In RUM based models, a decision maker, labelled s, faces a choice among P alternatives. The decision maker chooses the alternative that provides the greatest utility, where the utility is denoted U_{sp}. The researcher observes some attributes of the alternatives and some attributes of the decision maker and can therefore specify a function that relates these observed factors to the decision maker's utility. This function is often called the representative or systematic utility and is denoted V_{sp}. Since there are some aspects of utility that the researcher does not observe, utility is decomposed as $U_{sp} = V_{sp} + \varepsilon_{sp}$, where ε_{sp} captures the factors that affect utility but are not included in V_{sp}. Since the researcher does not know $\varepsilon_{sp}\ \forall\ p$, these terms are treated as random. If it is assumed that ε_{sp} is independently and identically distributed (iid) extreme value type 1 (Gumbel) for all p, the most commonly used Multinomial Logit (MNL) model can be derived (Train, 2009), which has a closed-form expression for the resulting choice probabilities:

$$P_{sr} = \frac{e^{V_{sr}}}{\sum_{p=1}^{P} e^{V_{sp}}} \tag{24}$$

where P_{sr} is the probability that decision maker s chooses alternative r. Representative or systematic utility is commonly specified to be linear in parameters, $V_{sp} = \beta' \mathrm{x}_{sp}$, where x_{sp} is a vector of observed variables relating to alternative p. With this specification, the MNL choice probabilities become:

$$P_{sr} = \frac{e^{\boldsymbol{\beta}' \mathbf{x}_{sr}}}{\sum_{p=1}^{P} e^{\boldsymbol{\beta}' \mathbf{x}_{sp}}} \tag{25}$$

In this research, modal split analysis is based on fixed mode splits, since there are few inter-regional alternatives in Ontario, and mode shifts are not the focus of this study.

3.2.4. Traffic assignment

The fourth and last step of the FSM is traffic or route assignment. In this step, the procedure of assigning each trip to a path is done. In this research, the traffic assignment takes the form of a

User Equilibrium (UE) traffic assignment using the SOLA (Second-Order Linear Approximation) algorithm in EMME 4 software.

There are several methods used for traffic assignment, two of which are most common: User Equilibrium (UE) and System Optimal (SO). UE is based on Wardrop's first principal, which states that any driver cannot decrease his/her travel costs by switching to other paths. Unfortunately, self-optimization does not lead to the minimum total travel time in the system. SO is based on Wardrop's second principal, which states drivers cooperate with one another to minimize the system-wide total travel time (Sheffi, 1984). Also commonly used is a "shortest path assignment", which does not consider congestion on used routes.

The following steps were followed for traffic assignment and generating results in EMME 4:

i. Adjustment of the OD matrices: it is assumed that the passenger demand is not impacted by trips to/from/between external zones, and thus the passenger OD matrix is a 49 x 49 matrix representing Ontario's internal trips for passenger cars. For trucks, however, the impact of external zones are considered. The OD matrix for truck demands was originally specified by a 75 x 75 matrix, but later the demands to/from zone #75 (New York via Peace Bridge or Lewiston-Queenston Bridge) were distributed equally between zones #72 and #74 (New York via Lewiston-Queenston Bridge and New York via Peace Bridge, respectively).
ii. Set up the truck class: the initial EMME model did not have trucks specified as a separate class. The class was defined in the model and the truck mode was allowed to use all roads in the network. After defining the new class, the demand matrices were assigned to their respective classes in the traffic assignment.
iii. Define output matrices: to store the results of the traffic assignment, three matrices were defined for each assignment to save truck volumes, passenger car volumes, and travel times reported at the link level. To compare these simulated measures to those of observed values, the link level data were aggregated to larger segments as needed.
iv. Traffic assignment: the Second-Order Linear Approximation (SOLA) algorithm was used in EMME to run the traffic assignment because of its ability to converge quickly and hence reduce the assignment run time compared to other traffic assignment procedures. As

mentioned earlier, the resulting travel times and traffic volumes were saved to predefined matrices to be used for comparison purposes.

4. Data collection and analysis for Ontario transportation network

In this chapter, travel demand data for Ontario transportation network is explained. In the first part, the data collection for trip generation is explained, and in the second part, data collection for freight demands are presented. Finally, two examples of freight demands which show two different situations for the location of the site (is a border crossing or not) are investigated.

4.1. Trip generation

For trip generation, data on the number of trips produced and attracted from or to a sample of CDs are required, as well as explanatory variables such as population and total number of households. The number of trips produced and attracted for 14 CDs are available in the Transportation Tomorrow Survey (TTS) ("Data Management Group – Introduction,"), and data for Population and number of households for 49 CDs are available in Statistics Canada, 2011 ("Statistics Canada: Canada's national statistical agency,").

The TTS collects typical household travel data in the Greater Toronto Area (GTA) that are needed for planning the development of the transportation system for all road users. Local and provincial agencies are working together to collect data. They select households to complete the survey randomly, and then send them an email or a phone call. The selected households can complete the survey online or on the phone which takes only 10 minutes. The TTS is interested in collecting data from all residents who use any mode of transportation. The goal of TTS is knowing where people are going and how they get their destination. These data has been collected every 5 years since 1986. ("Transportation Tomorrow Survey 2016,"). The latest available data is related to 2016 but because this research started in 2015, the data for 2011 is used. Table 4-1 shows some of the available data for 14 CDs. Figure 4-1and Figure 4-2 show data for population and households for some of the 49 CDs, respectively. Figure 4-3 shows data for trip production and trip attraction for 14 CDs.

Table 4-1- Data of 14 CDs of Ontario

	CD	Population	Total Number of households	Trip production	Trip attraction
1	Halton	501669	125085	1083200	1083100
2	Simcoe	446063	109845	489700	491600
3	Brantford	135501	39030	202400	202600
4	Hamilton	519949	116905	1045700	1046400
5	York	1032524	255475	2121600	2121700
6	Durham	608124	143800	1207500	1207200
7	Waterloo	507096	120465	1105100	1105400
8	Dufferin	56881	13945	40400	40500
9	Wellington	208360	51170	94400	94400
10	Kawartha Lakes	73214	19485	127300	128800
11	Toronto	2615060	543355	5588800	5592800
12	Niagara	431346	103060	932400	933000
13	Peterborough	134933	33520	207800	208000
14	Peel	1296814	302205	2624300	2615100

Source: Transportation Tomorrow Survey 2011 and Data Management Group 2011

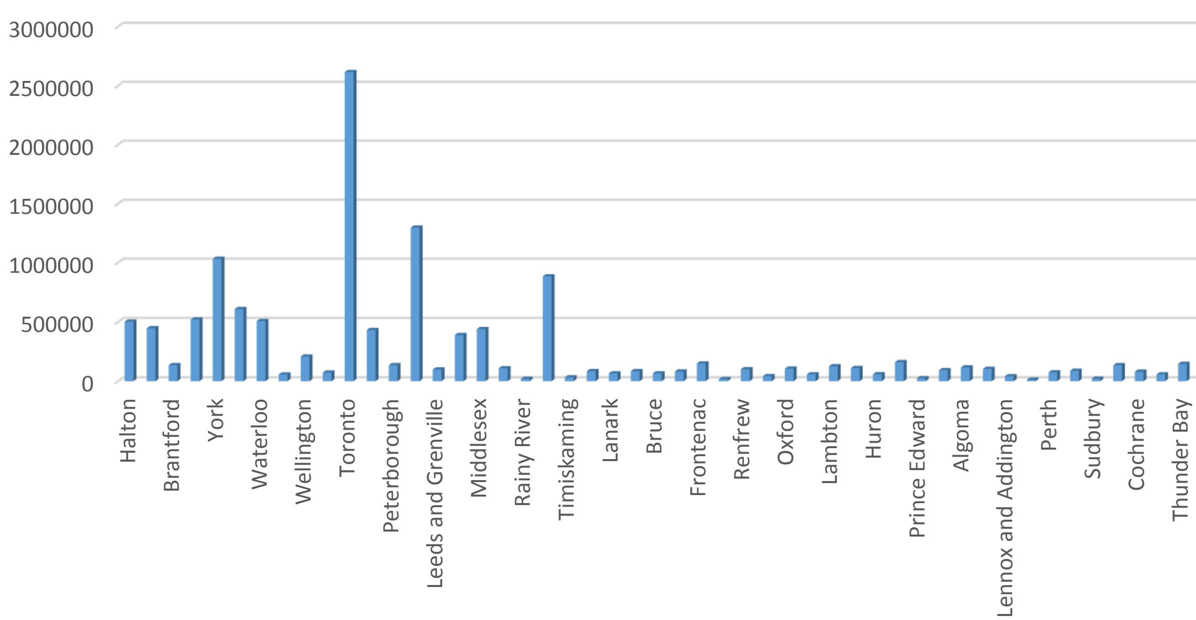

Figure 4-1- Population of some of the 49 CDs in Ontario

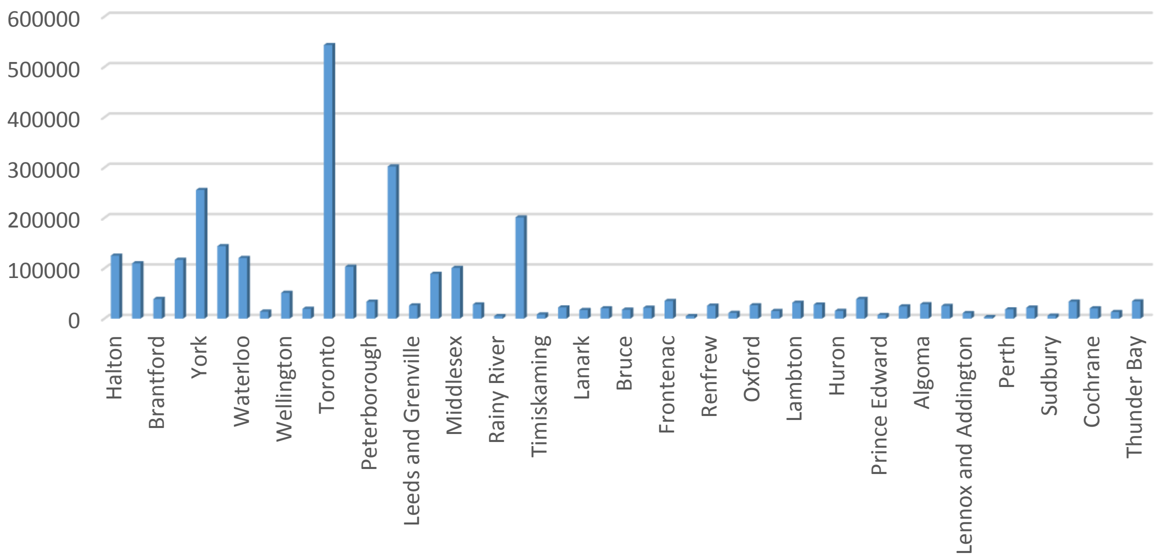

Figure 4-2- Total number of household of some of the 49 CDs in Ontario

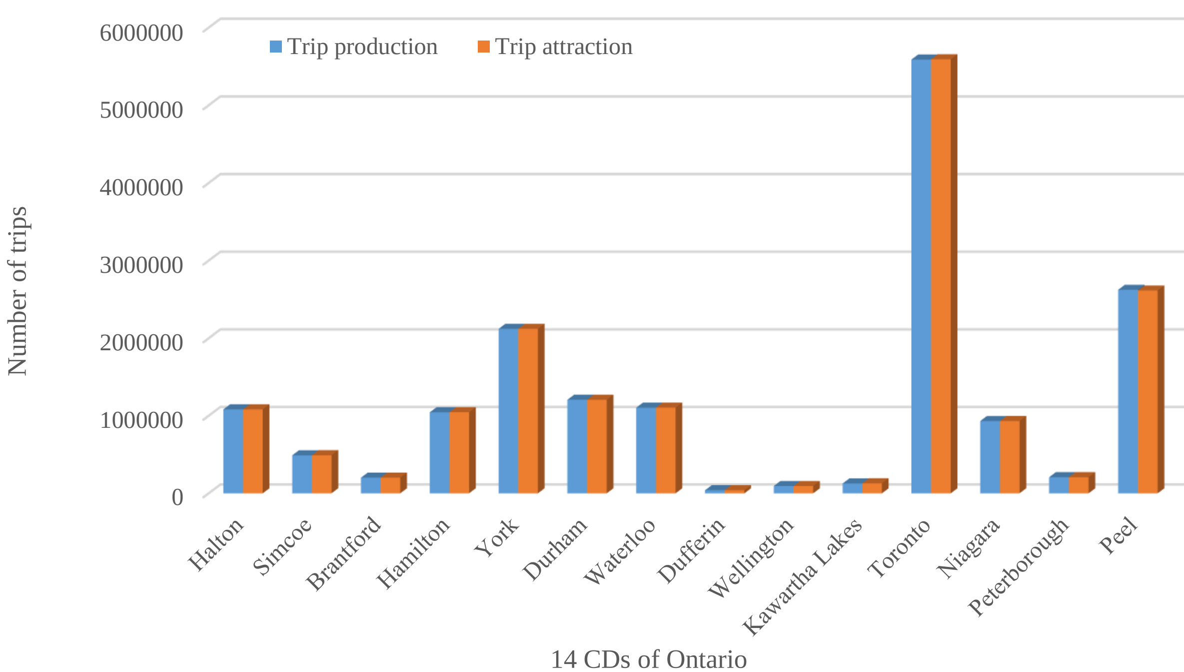

Figure 4-3- Trip production and trip attraction of 14 CDs in Ontario

4.2. **Freight demands**

Ministry of Transportation of Ontario (MTO) Commercial Vehicle Survey (CVS) is the most extensive freight travel survey in Ontario. The MTO CVS has been conducted over 150 road-side sites in Ontario and 10 sites in the GTHA every 5 years since 1995. The latest data is collected in 2012 which used in this research. Truck drivers use tablet applications to report attributes of the trip, carrier, commodity, vehicle, precision, origin and destination the route. These data reflected total 7-day continuous traffic. This survey considered only the trucks a Gross Vehicle Weight (GVW) of 4500 kg or over and other vehicles are not sampled. (Roorda, Taha Rashidi, & Bachmann Malvika Rudra, 2013)

4.2.1. Total truck OD matrix

Each record in the MTO CVS was multiplied by the National Weight for Expansion (NW), defined by the MTO as "The value for national expansion weight, taking into account trips passing each Data Collection Site (DCS) and not site-specific but suitable for global analysis of the data." Since this factor is used to estimate equivalent weekly trips from each record, it was divided by 7 to determine equivalent daily trips. Therefore, the number of daily truck trips ($\mathrm{dt_k}$) from each record (*k*) was estimated by equation (26).

$$dt_k = \frac{NW_k}{7} \tag{26}$$

Origin and destination CDs for daily truck trips were determined from the Trip Origin Ontario CVS Zone (H04TOZONE) and the Trip Destination Ontario CVS Zone (H06TDZONE) data fields. Note that CVS Zones are Census Subdivisions (CSDs) in Canada and Federal Information Processing Standard (FIPS) zones in the US. CSDs in Ontario were aggregated into their 49 CDs. For now, all trip origins and destinations outside of the 49 CDs of Ontario were aggregated into one zone ("External"). Therefore, the total number of daily truck trips ($\mathrm{tt_{ij}}$) between an origin and destination pair of CDs (*ij*) was determined by summing the daily truck trips for each record *k* belonging to the OD pair (equation 27).

$$tt_{ij} = \sum_{k \in ij} dt_k \tag{27}$$

4.2.2. Cargo-carrying truck OD matrix

Records carrying cargo are identified in the data field F01CARGO, defined by the MTO as "Whether the truck is carrying cargo." Cargo-carrying trucks were aggregated to include those with the following F01CARGO attribute: Y = Yes; and V = Vehicle commodity (vehicle and/or trailer itself is the commodity being delivered). Using a cargo status dummy variable (CS_k= 1 if record k is carrying cargo; 0 otherwise), the number of cargo-carrying truck trips (Ct_{ij}) was determined by equation 28.

$$ct_{ij} = \sum_{k \in ij} dt_k \, cs_k \tag{28}$$

4.2.3. Empty truck OD matrix

Similarly, records not carrying cargo are also identified in the data field F01CARGO. Empty trucks were defined as those with the following F01CARGO attribute: YC = Carrying containers only; YT = Carrying company tools; N = No Cargo (empty); S = Non Cargo Carrying Truck; and NR= No Response. Using the same cargo status dummy variable (cs_k= 1 if record k is carrying cargo; 0 otherwise), the number of empty truck trips (et_{ij}) was determined by equation 29.

$$et_{ij} = \sum_{k \in ij} dt_k \, (1 - cs_k) \tag{29}$$

Note that total daily truck trips are the sum of cargo-carrying truck trips and empty truck trips (equation 30).

$$tt_{ij} = ct_{ij} + et_{ij} \tag{30}$$

4.2.4. Value ($) OD matrix

The daily value ($) of goods travelling between each OD pair was estimated using the Value of Commodity (F11COMVAL) associated with each record. This commodity value in Canadian dollars is based on the total weight of the goods and the per kilogram value of the goods from the Per-Kilogram Value of Commodity on Board (F11SCTGKGVAL). Note that the per-kilogram value of a specific commodity (using SCTG codes) is assumed based on international trade data.

Therefore, the value of total daily truck trips (vt_{ij}) between each OD pair (ij) was estimated by equation 31.

$$vt_{ij} = \sum_{k \in ij} dt_k \times F11COMVAL_k \qquad (31)$$

4.2.5. Daily truck trip attractions and productions

For future trip generation models (outside the scope of this thesis), total daily truck trip attractions and productions were calculated from the total truck OD matrix. Total daily truck trip attractions (a_j) for each destination (j) are calculated as a column sum of the OD matrix (equation 32).

$$a_j = \sum_i tt_{ij} \qquad (32)$$

Similarly, total daily truck trip productions (p_i) for each origin (i) are calculated as a row sum of the OD matrix (equation 33).

$$p_i = \sum_j tt_{ij} \qquad (33)$$

These daily total truck trip attractions and productions can be used to estimate truck trip generation models to establish a relationship between truck trips and other sociodemographic variables (e.g., population, employment). These models are not needed for an analysis of current regional truck trips in Ontario because of the relatively recent MTO CVS data, but would be useful for future scenario analysis (e.g., forecasting population and/or employment growth).

4.2.6. Internal trips

The estimation of hourly truck trips is based on traffic count data from the Ministry of Transportation of Ontario ("Ontario Provincial Highways Traffic Volumes On Demand," n.d.). Hourly truck factors per CD were derived from hourly truck traffic count information collected at a number of stations distributed throughout the province. Each CD was assigned one or more traffic count stations based on their locations. If a CD did not have a station located in it, the closest station was assigned. Using the collected data, an hourly distribution per CD is generated based on averaging the hourly truck trips of all the stations located with the CD (see Table A.1 in

Appendix A). The hourly factor for each hour of the day is then applied to the daily truck OD matrix to create the hourly OD matrices for the CDs.

4.2.7. External trips

External trips are those that have an origin or destination outside of Ontario. External trips also include those that pass through Ontario without stopping (e.g., from New York to Quebec). Based on the 2012 MTO CVS, external trips represent approximately 22% of all daily truck trips in Ontario (i.e., 28,237 of 130,412 daily trips). By value, external trips represent 50% of the total daily commodity value moved throughout Ontario (i.e., $1,256,675,835 of the $2,519,310,316 of goods moved through Ontario each day). Due to their high proportion of total truck trips and substantial contribution to the total value of goods moving throughout Ontario, external trips must be considered when modelling freight flows on the transportation network. Hence, external zones connected to Ontario border crossings must be identified for inclusion in the Ontario network model to comprehensively analyze freight flows in Ontario.

External trips were processed differently than internal trips. Recall that origins and destinations for internal trips were determined from the Trip Origin Ontario CVS Zone (H04TOZONE) and the Trip Destination Ontario CVS Zone (H06TDZONE) data fields (which are Census Subdivisions (CSDs) in Canada). For external trips, an Ontario border crossing cannot be identified with certainty from the origin or destination CVS Zone (which are Federal Information Processing Standard (FIPS) zones in the US) because there are multiple and competing routes and border crossing alternatives. For this reason, the specific route of each external truck trip was analyzed to determine the border crossing(s).

The Points of Interest (POIs) passed by each external truck trip were analyzed to determine border crossing(s). All points of interest passed (H17POIPALL) is an array of POIs passed by each truck, including truck inspection stations, maintenance yards, parking lots, and border plazas. The first POI passed was used to determine an origin border crossing for trips beginning outside of Ontario, and the last POI passed was used to determine a destination border crossing for trips ending outside of Ontario; both the first and last POI passed were used to determine border crossings for trips beginning and ending outside of Ontario. In some cases, the first or last POI is a border plaza, which makes the identification of a border crossing trivial (i.e., the POI is the border crossing). In other cases, the first or last POI is not a border plaza and the border crossing was estimated by the closest border crossing to the POI and by examining the shortest path to the origin or destination of the trip (explained in the second example below). In total, 26 external border crossings were identified for inclusion as external zones in the Ontario network model as listed in Table 4-2.

Table 4-2- External gateways into and out of Ontario

# (FIRST 49 ZONES ARE ONTARIO CDS)	DESCRIPTION
50	Quebec via HWY 101
51	Quebec via HWY 66
52	Quebec via HWY 65
53	Quebec via HWY 63
54	Quebec via HWY 653
55	Quebec via Chaudière Bridge
56	Quebec via Macdonald-Cartier Bridge
57	Quebec via Hawkesbury Bridge
58	Quebec via HWY 417
59	Quebec via HWY 401
60	Manitoba via HWY 17
61	Minnesota via Rainy River Bridge
62	Minnesota via Fort Frances Bridge
63	Minnesota via Pigeon River Border
64	Michigan via Sault Ste. Marie Bridge
65	Michigan via Bluewater Bridge
66	Michigan via Ambassador Bridge
67	Michigan via Windsor-Detroit Tunnel
68	Michigan via Windsor-Detroit Ferry
69	New York via Seaway International Bridge
70	New York via Prescott Bridge
71	New York via Thousand Islands Bridge
72	New York via Lewiston-Queenston Bridge
73	New York via Rainbow Bridge
74	New York via Peace Bridge
75	New York via Peace Bridge or Lewiston-Queenston Bridge

4.3. Examples for freight demands

4.3.1. Example: First or last data collection site is a border crossing

An example trip begins in Aurora, Ontario (H04TOZONE = 3519046) and ends in Toledo, Ohio (H06TDZONE = 7039095). This trip begins in an Ontario CD, which is identified by the Trip Origin Ontario CVS Zone (H04TOZONE) as Zone #18 (York). However, since the trip ends in Ohio, the border crossing cannot be identified from the Trip Destination Ontario CVS Zone (H06TDZONE). Instead, it can be identified from all points of interest passed (H17POIPALL). The array of POIs indicates the last POI passed was "ON0291", which corresponds to the Ambassador Bridge (Westbound) data collection site. Therefore, this external trip originates in Zone #18 (York) and terminates at Zone #66 (Michigan via Ambassador Bridge).

4.3.2. Example: First or last data collection site is not a border crossing

An example trip begins in St. Lawrence County, New York and ends in Thurso, Quebec. Since both trip-ends are external, border crossings into and out of Ontario can be identified from all points of interest passed (H17POIPALL). The array of POIs indicates the first POI passed was "ON0282", which corresponds to the Seaway International Bridge (Northbound) data collection site. Therefore, the trip originates at Zone #69 (New York via Seaway International Bridge). The last POI passed was "ON0550", which corresponds to the Monkland (Northbound) data collection site, located on Highway 138, 550m south of Route 43. Since the last POI passed is not a border plaza, the border crossing needs to be estimated by the closest border crossing to the last POI and by examining the shortest path to the trip destination. There are several nearby border crossings into Quebec, including: Chaudière Bridge (Zone #55), Macdonald-Cartier Bridge (#56), Hawkesbury Bridge (#57), Hwy 417 (#58), and Hwy 401 (#59). To estimate the border crossing, the shortest path (128km) from the last POI (Monkland, Northbound) to the destination (Thurso, Quebec) was found to use the Hawkesbury Bridge (#57) border crossing. Therefore, this external trip originates in Zone #69 (New York via Seaway International Bridge) and terminates at Zone #57 (Quebec via Hawkesbury Bridge).

External zones rely on the hourly factor for the CD in which they are located. Table 4-3 shows the correspondence between external zones and their corresponding CD.

Table 4-3- External Zones and Corresponding Census Division

External Zone		Location (Census Division)	
Zone #	Description	Zone #	Description
50	Quebec via HWY 101	26	Stormont, Dundas and Glengarry
51	Quebec via HWY 66	9	Timiskaming
52	Quebec via HWY 65	9	Timiskaming
53	Quebec via HWY 63	14	Nipissing
54	Quebec via HWY 653	20	Renfrew
55	Quebec via Chaudière Bridge	8	Ottawa
56	Quebec via Macdonald-Cartier Bridge	8	Ottawa
57	Quebec via Hawkesbury Bridge	10	Prescott and Russell
58	Quebec via HWY 417	10	Prescott and Russell
59	Quebec via HWY 401	26	Stormont, Dundas and Glengarry
60	Manitoba via HWY 17	48	Kenora
61	Minnesota via Rainy River Bridge	7	Rainy River
62	Minnesota via Fort Frances Bridge	7	Rainy River
63	Minnesota via Pigeon River Border	49	Thunder Bay
64	Michigan via Sault Ste. Marie Bridge	33	Algoma
65	Michigan via Bluewater Bridge	24	Lambton
66	Michigan via Ambassador Bridge	2	Essex
67	Michigan via Windsor-Detroit Tunnel	2	Essex
68	Michigan via Windsor-Detroit Ferry	2	Essex
69	New York via Seaway International Bridge	26	Stormont, Dundas and Glengarry
70	New York via Prescott Bridge	1	Leeds and Grenville
71	New York via Thousand Islands Bridge	1	Leeds and Grenville
72	New York via Lewiston-Queenston Bridge	42	Niagara
73	New York via Rainbow Bridge	42	Niagara
74	New York via Peace Bridge	42	Niagara
75	New York via Peace Bridge or Lewiston-Queenston Bridge	42	Niagara

5. Ontario’s travel demand model results

In this chapter, the results of developing an Ontario travel demand model are presented. In the first part of this chapter, the results for linear regression which determines the number of trip produced and attracted are shown. In the second part, the results of trip distribution are demonstrated. In the third part, the description and results of demand adjustment are explained. In the last part of this chapter, results for validating the model are demonstrated by showing the correlation coefficients for travel time and volumes.

5.1. Trip generation (Linear regression)

Once the linear regression based on the data for 14 CDs and explained in Chapter 3 has been done, the coefficients for trip production and trip attraction can be obtained. Table 5-1 shows a summary of linear regression results for the 14 CDs for trip production. As shown in Table 5-1, number of households has the negative coefficient and unacceptable t-stat amount in the first estimation with a constant (considering Population and Households). By comparing the first and second model (Population without intercept and population with intercept), because adjusted R-squared variable in the second model (0.99) is more than the first one (0.92), the second model is selected. Therefore, the model with the best fit includes population (with constant), with the coefficient of 2.17 and the intercept of -125776.14 for trip production and the intercept of -125795.86 for trip attraction. The t-statistics indicate that this coefficient is statistically significant at a 95% confidence level and its value for 14 observations based on the t-stat table is 1.76 or more. Adding an additional explanatory variable (number of households) does not improve the model.

Table 5-1- Summary of linear regression results for Trip Production for 14 CDs in Ontario

	# Regression	Variables	Coefficient	Standard Error	t Stat	P-Value	R Square	Adjusted R Square
Trip Production without constant	1	Population	3.17	0.64	4.93	0.00	0.99	0.91
		Total Number of households	-4.99	2.92	-1.71	0.11		
	2	Population	2.08	0.05	41.62	0.00	0.99	0.91
	3	Total Number of households	9.38	0.35	26.53	0.00	0.98	0.90
Trip Production with constant	1	Intercept	-107222.16	70693.07	-1.52	0.16	0.99	0.99
		Population	2.49	0.76	3.26	0.01		
		Total Number of households	-1.48	3.61	-0.41	0.69		
	2	**Intercept**	**-125776.14**	**52403.83**	**-2.40**	**0.03**	**0.99**	**0.99**
		Population	**2.17**	**0.06**	**37.13**	**0.00**		
	3	Intercept	-244742.09	76245.24	-3.21	0.01	0.98	0.98
		Total Number of households	10.26	0.39	26.56	0.00		

Table 5-2- Summary of linear regression results for Trip Attraction for 14 CDs in Ontario

	# Regression	Variables	Coefficient	Standard Error	t Stat	P-Value	R Square	Adjusted R Square
Trip Attraction without constant	1	Population	3.19	0.64	4.97	0.00	0.99	0.91
		Total Number of households	-5.07	2.91	-1.74	0.11		
	2	Population	2.08	0.05	41.57	0.00	0.99	0.92
	3	Total Number of households	9.38	0.35	26.45	0.00	0.98	0.90
Trip Attraction with constant	1	Intercept	-105431.10	70705.04	-1.49	0.16	0.99	0.99
		Population	2.52	0.76	3.30	0.01		
		Total Number of households	-1.63	3.61	-0.45	0.66		
	2	**Intercept**	**-125795.86**	**52493.27**	**-2.40**	**0.03**	**0.99**	**0.99**
		Population	**2.17**	**0.06**	**37.07**	**0.00**		
	3	Intercept	-244633.96	76712.20	-3.19	0.01	0.98	0.98
		Total Number of households	10.26	0.39	26.40	0.00		

Table 5-3 shows the estimated dataset for all 49 CDs in Ontario, by applying the coefficients from Table 5-1 and Table 5-2 in for this research:

$$\text{Trip Production} = 2.17\ (\text{Population}) - 125776.14 \quad (34)$$
$$\text{Trip Attraction} = 2.17\ (\text{Population}) - 125795.86 \quad (35)$$

The first 14 CDs listed in Table 5-3 show observed trip production and attraction totals, whereas the remaining CDs show estimated trip production and attraction totals.

Table 5-3- Data for all census divisions (CDs)

	CD	Population	Total Number of households	Trip production	Trip attraction
1	Halton	501669	125085	1083200	1083100
2	Simcoe	446063	109845	489700	491600
3	Brantford	135501	39030	202400	202600
4	Hamilton	519949	116905	1045700	1046400
5	York	1032524	255475	2121600	2121700
6	Durham	608124	143800	1207500	1207200
7	Waterloo	507096	120465	1105100	1105400
8	Dufferin	56881	13945	40400	40500
9	Wellington	208360	51170	94400	94400
10	Kawartha Lakes	73214	19485	127300	128800
11	Toronto	2615060	543355	5588800	5592800
12	Niagara	431346	103060	932400	933000
13	Peterborough	134933	33520	207800	208000
14	Peel	1296814	302205	2624300	2615100
15	Leeds and Grenville	99,306	26,185	90180	90164
16	Essex	388,782	88,980	719692	719684
17	Middlesex	439,151	100,655	829227	829222
18	Haldimand-Norfolk	109,118	28,110	111518	111502
19	Rainy River	20,370	4,935	81478	81497
20	Ottawa	883,391	200,930	1795298	1795306
21	Timiskaming	32,634	8,265	54808	54826
22	Prescott and Russell	85,381	22,160	59898	59881
23	Lanark	65,667	17,070	17027	17009
24	Nipissing	84,736	20,585	58495	58478

25	Bruce	66,102	17,760	17973	17955
26	Northumberland	82,126	21,705	52819	52802
27	Frontenac	149,738	35,140	199852	199838
28	Haliburton	17,026	4,945	88750	88769
29	Renfrew	101,326	25,790	94573	94556
30	Parry Sound	42,162	11,460	34088	34106
31	Oxford	105,719	26,530	104126	104110
32	Muskoka	58,047	15,150	456	438
33	Lambton	126,199	31,545	148663	1486483
34	Stormont, Dundas and Glengarry	111,164	27,835	115967	115951
35	Huron	59,100	15,415	2746	2728
36	Greater Sudbury / Grand Sudbury	160,376	39,035	222986	222972
37	Prince Edward	25,258	7,145	70848	70867
38	Grey	92,568	24,195	75527	75510
39	Algoma	115,870	28,605	126201	126185
40	Chatham-Kent	104,075	25,360	100551	100535
41	Lennox and Addington	41,824	11,020	34823	34841
42	Manitoulin	13,048	3,135	97401	97420
43	Perth	75,112	18,440	37566	37549
44	Elgin	87,461	21,795	64421	64404
45	Sudbury	21,196	5,900	79682	79701
46	Hastings	134,934	33,750	167659	167643
47	Cochrane	81,122	20,380	50636	50619
48	Kenora	57,607	13,175	500	518
49	Thunder Bay	146,057	34,375	191848	191833

5.2. Trip distribution

After completing the trip generation step and preparing the dataset (Table 5-3), trip distribution can be completed. The Haversine formula described in Chapter 3 (for finding the distances between zones) is used to provide the matrix of inter-CD distances.

- Finding the number of trips between origin i and destination j (Tij)

After calculating the distances, the T_{ij} matrix, which is the trip distribution matrix, can be obtained using the gravity model equation. First, linear regression is used to estimate the parameters of the gravity model (equation 36). Table 5-4 shows the results of the parameter estimates for the gravity model of trip distribution.

Table 5-4- Linear regression results for gravity model

	Coefficients	Standard Error	t Stat	P-value	R Square	Adjusted R Square	Observations
Intercept	-21.18	3.16	-6.69	0.00	0.54	0.53	196
Ln(Vi)	1.23	0.16	7.45	0.00			
Ln(Wj)	1.16	0.16	7.02	0.00			
dij	-0.02	0.00	-7.65	0.00			

Based on the results from Table 5-4, the equation for T_{ij} is:

$$LnT_{ij} = -21.18 + (1.23)LnV_i + (1.16)LnW_j + (-0.02)d_{ij} \quad (36)$$

Therefore, by replacing the data for V_i (population of zone *i*), W_j (population of zone *j*), and d_{ij} (distance between zones *i* and *j*) in equation 36, the T_{ij} values are obtained. Figure 5-1 and Figure 5-2 show the comparison graphs based on the results estimated from the gravity model (Predicted) and data from the Transportation Tomorrow Survey ("Data Management Group – Introduction," n.d.) (Observed) for trip production and trip attraction, respectively. As shown in Figure 5-1 and Figure 5-2, the slope of these two graphs are 0.87, which is near to 1 which demonstrates that the predicted results are underestimated but well correlated. To have more accurate results, the T_{ij} matrix can be revised. To revise the results, matrix balancing is done based on the method described in Chapter 3, and it must be repeated to until the total trip productions and attractions from the trip distribution matrix (T_{ij}), match the previously estimated totals from the trip generation models. In this research, matrix balancing was repeated 15 times until complete convergence was reached. Figure 5-3 and Figure 5-4 show the comparison graphs for trip production and trip attraction, respectively. As shown in Figure 5-3 and Figure 5-4, the slope of Predicted-Observed graph is exactly 1 and the R-Squared amounts are 0.9999, which is reasonably close to 1, demonstrating that all of the data are fitted to the regression line.

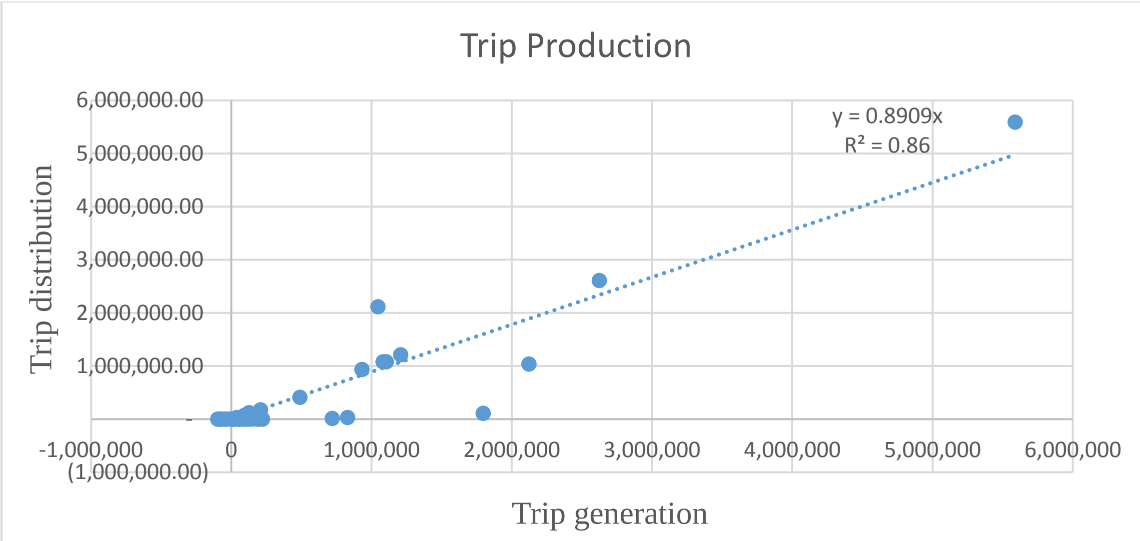

Figure 5-1- The comparison graph for trip production before balancing

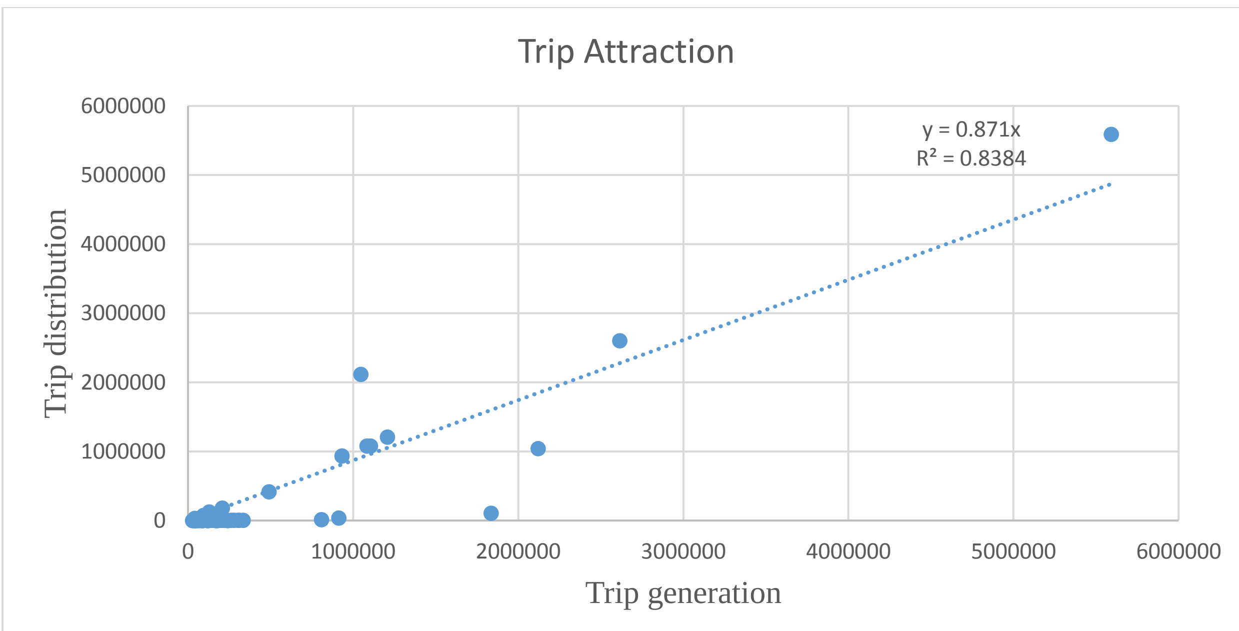

Figure 5-2- The comparison graph for trip attraction before balancing

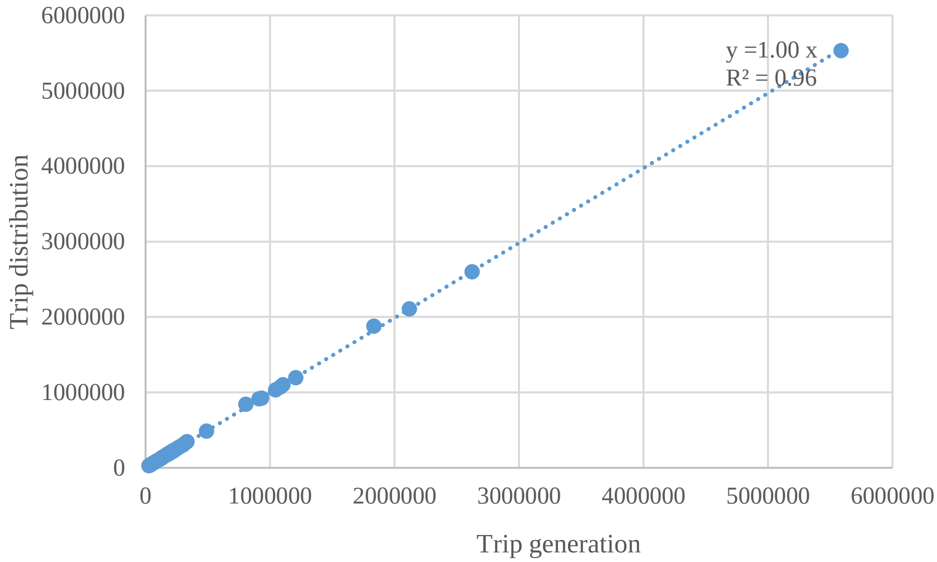

Figure 5-3- The comparison graph for trip production after balancing

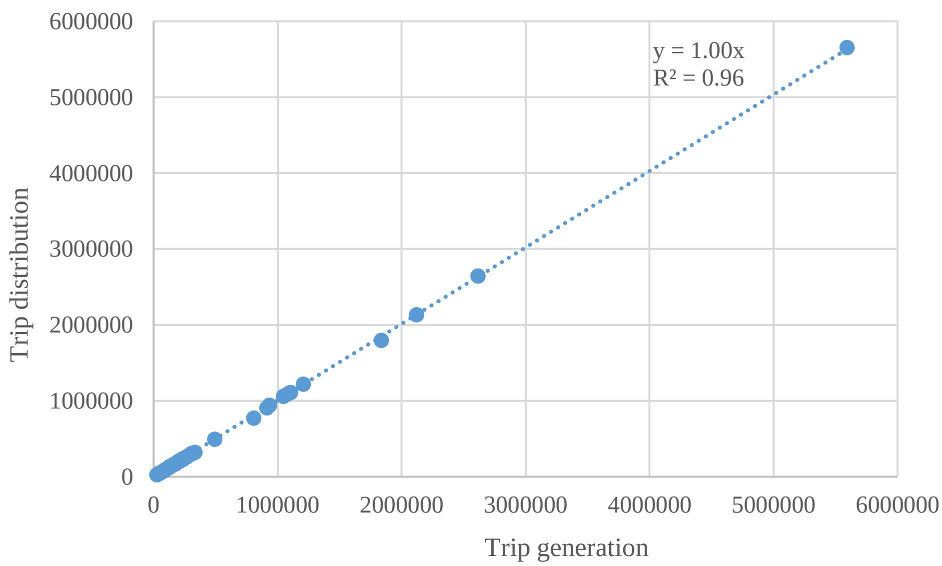

Figure 5-4- The comparison graph for trip attraction after balancing

5.3. Mode choice

According to the 2011 Canadian Census, the average percentage of auto work trips was 87.5%. Removing the outlier cases (i.e., Toronto and Ottawa with 52.9% and 66.7% auto shares, respectively) results in an average percentage of 89% in automobile work trips. This mode share can be used to scale the estimated trips for the 49 census divisions. Hourly factors are derived from hourly traffic count data from the MTO, as described for freight demands above.

5.4. Demand adjustment

5.4.1. Description

Final passenger demand estimates were compared with those estimated by Ghamrawi et al. (2016). Their initial methodology was the same as above (i.e., same data sources and model types), but adjustments were later made to the PM Peak estimates to overcome nonsensible results. More specifically, the flows destined to Toronto in the PM Peak period appear to be higher than the flows leaving Toronto. Note that Toronto tends to attract traffic in the morning but should exhibit the opposite trend in the PM Peak. They concluded the initial estimates above are acceptable at the aggregate (24 hours) level but need to be revised to make sure the hourly disaggregation produce sensible results. They developed a more elaborate methodology which produced superior passenger demand estimates (in the sense that nonsensible results were minimized), which were then adopted in this research.

Observed traffic count data were provided in a GIS database. From that database, the records for peak hours in the morning and afternoon (8:00AM to 9:00AM and 5:00PM to 6:00 PM) were extracted for both trucks and passenger cars. The travel time data were provided in excel sheets on a segment basis (i.e., each highway is divided into smaller segments and the travel time is provided for each segment). The corresponding node IDs from EMME is extracted for each of these travel time records. For the observed traffic volumes, a small portion of the GIS records do not contain the corresponding EMME nodes in the records; those records are not included in this comparison and will be added in the next steps of the project.

To better fit the demands to observed traffic volumes and travel times, automated demand adjustments were then implemented in EMME. This approach works well for short-term applications but is unsuitable for medium and long-term demand forecasting. Successful demand-adjustment methods require knowing whether observed and assigned volumes differ because of the demand matrix. If instead, errors arise, they can be due to coding errors in traffic or transit networks, wrong counts or poor volume delay calibration. Prior to adjustment, data must be thoroughly analyzed, and the adjusted O-D matrices must be examined using EMME's matrix and tools.

The quality of the model fit is evaluated by correlation coefficients, sometimes called cross-correlation coefficients. The range of values for a correlation coefficient is between -1 and 1. A correlation coefficient of 1 represents a perfect positive correlation, while a correlation coefficient of -1 equals a perfect negative correlation, and a correlation coefficient of 0 indicates no linear relationship.

5.4.2. Comparison of simulation results with observed data before and after demand adjustment

To find out whether the demand adjustment could improve the model or not, a comparison graph with the R^2 statistic along with the fitted line equation was determined for both cases (before and after adjustment). R^2 can take the amounts from 0 to 1, $R^2 = 0$ shows that the model cannot explain any variation in the data and so it is not preferred. $R^2 = 1$ explains that all the variability of the simulated data around its mean. Ideally, the equation of the fitted line would be y = x (showing that observed and simulated data are the same). In reality, these amounts vary, as the models are less than perfectly accurate.

The comparison graphs and statistics for travel times for AM and PM hour are available in Appendices B.1 and B.2, respectively; and the comparison graphs and statistics for truck volumes for AM and PM are presented in Appendices B.3 and B.4, respectively. Moreover, the comparison graphs and statistics for passenger car volumes for AM and PM are presented in Appendices B.5 and B.6, respectively. In Appendices B.7 to B.14, the data for travel time, truck volume and passenger car volume for AM and PM peak hour before and after adjustment are presented.

5.5. Validation

5.5.1. Comparison of correlation coefficients for travel times

Table 5-5 shows the correlation coefficients for the travel times for all highways, other highways, and highways 401 EB, 401 WB, 407 EB, 407 WB, the QEW Toronto bound, and the QEW Niagara bound, before and after adjustment for the AM and PM hours. Note that other highways include all highways except highways 401, 407 and the QEW. As shown in Table 5-5, all correlation coefficients for the AM and PM hours are greater than 0.59, but the correlation coefficients for Highway 401 WB are negative (bolded), indicating modelled travel times are not representative of real-world conditions for this highway stretch. EMME's demand adjustments did not make substantial changes to the correlation coefficients.

Table 5-5- Correlation coefficient of travel times for all, other highways and highway 401, 407 and QEW for AM and PM hours before and after the adjustment

	# of Observations	AM Initial	AM Final	PM Initial	PM Final
All Highways	74	0.816	0.794	0.641	0.647
Other Highways	36	0.897	0.891	0.678	0.684
401 EB	9	0.694	0.604	0.597	0.604
401 WB	9	**-0.527**	**-0.659**	**-0.653**	**-0.659**
407 EB	4	0.978	0.980	0.831	0.832
407 WB	4	0.960	0.956	0.982	0.980
QEW (to Toronto)	5	0.910	0.907	0.907	0.907
QEW (to Niagara)	5	0.980	0.962	0.964	0.962

Figure 5-5 and Figure 5-6 show the predicted-observed graphs for initial travel times for AM and PM, respectively. As demonstrated in Figure 5-5, the predicted travel times are overestimated, whereas for PM, the predicted travel times are underestimated (Figure 5-6).

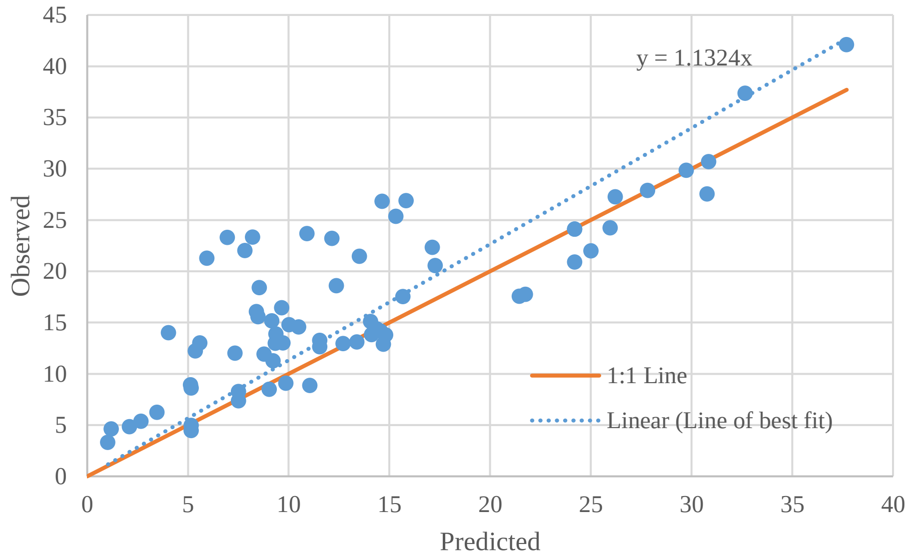

Figure 5-5- AM travel times

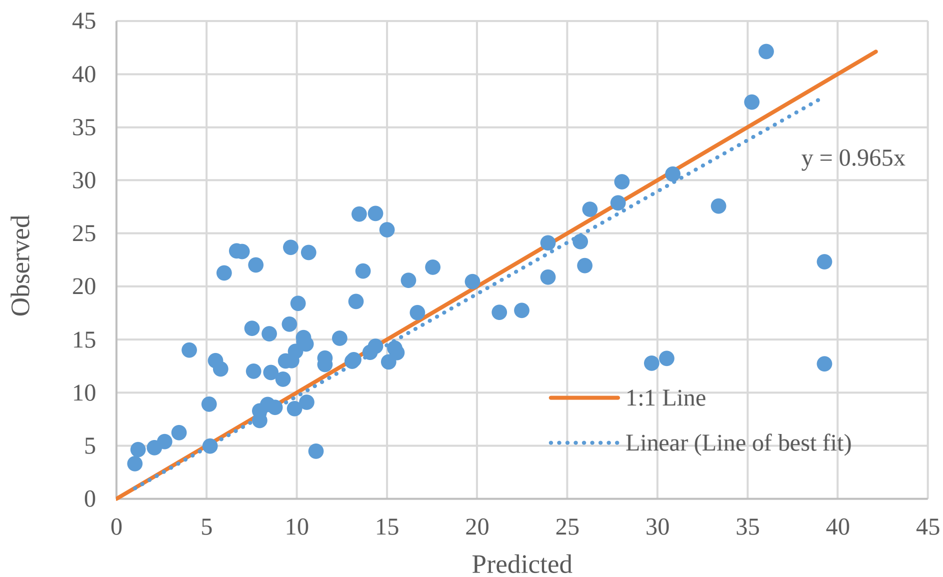

Figure 5-6- PM travel times

5.5.2. Comparison of correlation coefficients for traffic volumes

Table 5-6 and Table 5-7 show the correlation coefficients for all highways, other highways, and Highway 401, before and after adjustment, for the AM and PM hours, for the truck and passenger vehicle volumes. In this case, other highways include all highways except Highway 401. Since there were few truck count observations for Highways 407 and the QEW, they were not considered separately as they were in the previous section (travel times). As shown in Table 5-6, all correlation coefficients for truck volumes for the AM and PM hours for all highways and other highways are greater than 0.75. In addition, the coefficients for Highway 401 EB for the AM and PM hours are improved after adjustment (greater than 0.67), but the correlation coefficients for Highway 401 WB for the AM and PM hours are still problematic (bolded). Other correlation coefficients improve slightly after adjustment.

Table 5-6- Correlation coefficient of truck volumes for all, other highways and highway 401 for the AM and PM hours before and after the adjustment

	# of Observations	AM Initial	AM Final	PM Initial	PM Final
All Highways	49	0.757	0.824	0.733	0.815
Other Highways	37	0.778	0.778	0.867	0.867
401 EB	7	-0.056	0.677	0.572	0.850
401 WB	6	**0.206**	**0.090**	**-0.637**	**-0.493**

Figure 5-7 and Figure 5-8 show the Predicted-Observed graphs for initial truck volumes for AM and PM, respectively. Both graphs demonstrate that the predicted travel times are overestimated.

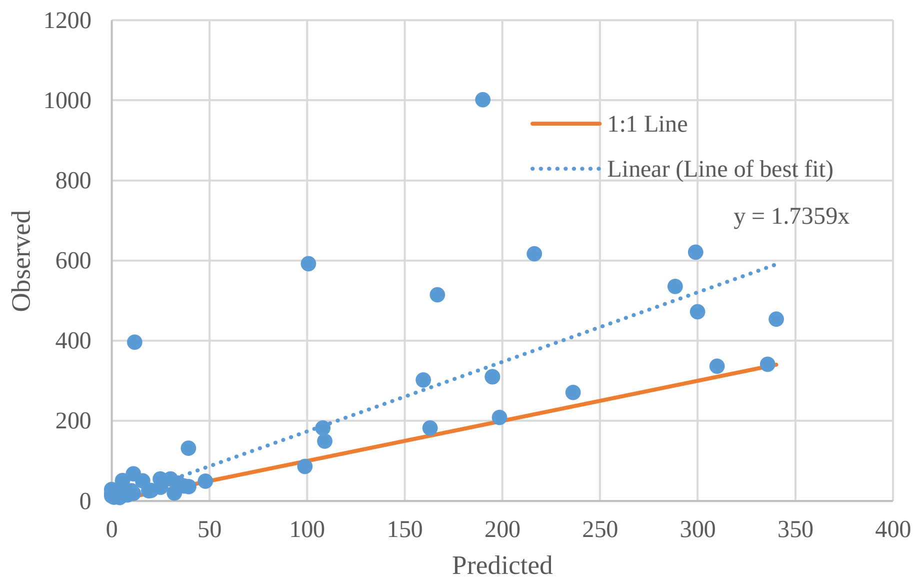

Figure 5-7-AM truck volumes

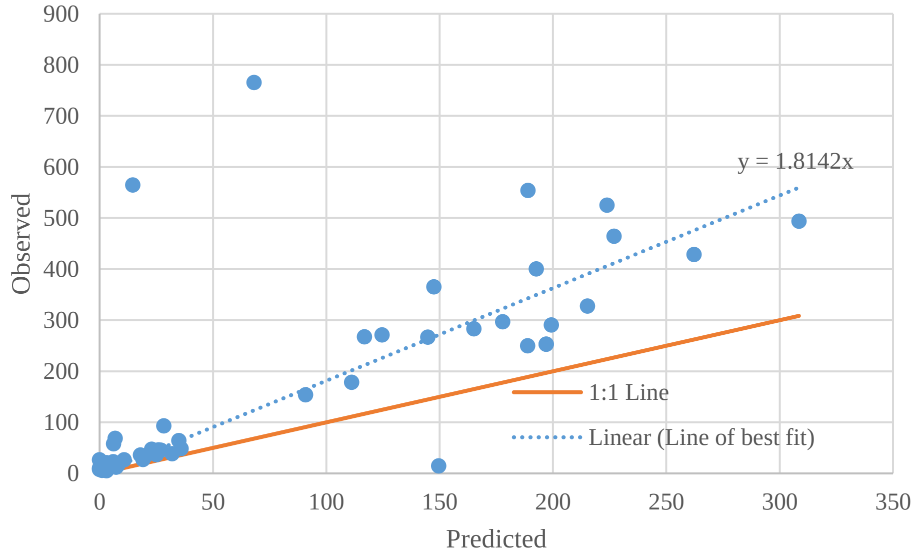

Figure 5-8- PM truck volumes

As shown in Table 5-7, all correlation coefficients for passenger vehicle volumes for the AM and PM hours for all highways and other highways are greater than 0.42. In addition, the coefficients for 401 EB for PM hours are greater than 0.43, but other correlation coefficients for Highway 401 WB for the AM and PM hours, and 401 EB for AM hours (highlighted in red), again indicating lower model fit on Highway 401. As before, EMME's demand adjustments did not make substantial changes to the correlation coefficients.

Table 5-7- Correlation coefficient of passenger vehicle volumes for all, other highways and highway 401 for the AM and PM hours before and after the adjustment

	# of Observations	AM Initial	AM Final	PM Initial	PM Final
All Highways	49	0.475	0.428	0.517	0.528
Other Highways	37	0.610	0.610	0.729	0.729
401 EB	7	**0.086**	**0.110**	0.439	0.466
401 WB	6	**-0.324**	**-0.574**	**-0.413**	**-0.417**

Figure 5-9 and Figure 5-10 show the Predicted-Observed graphs for initial passenger car volumes for AM and PM, respectively. Both graphs demonstrate that the predicted travel times are underestimated.

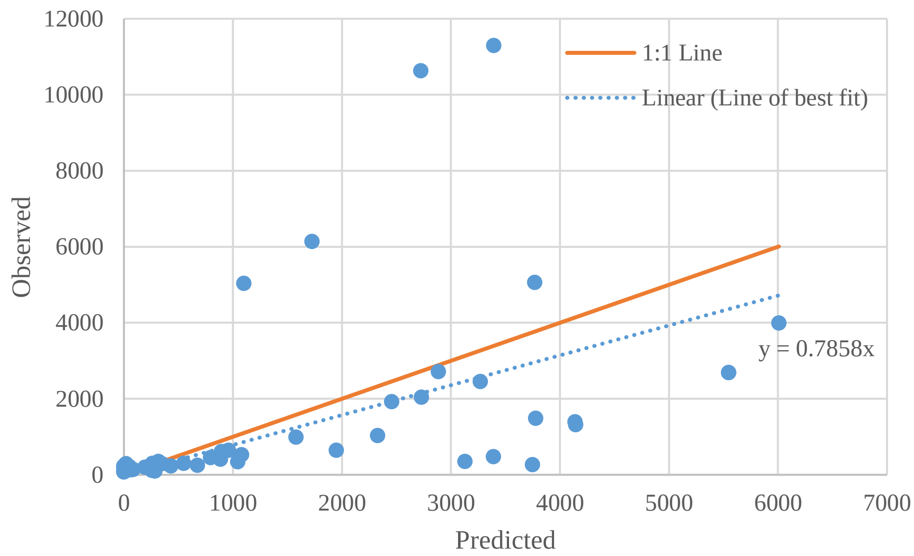

Figure 5-9- AM passenger car volumes

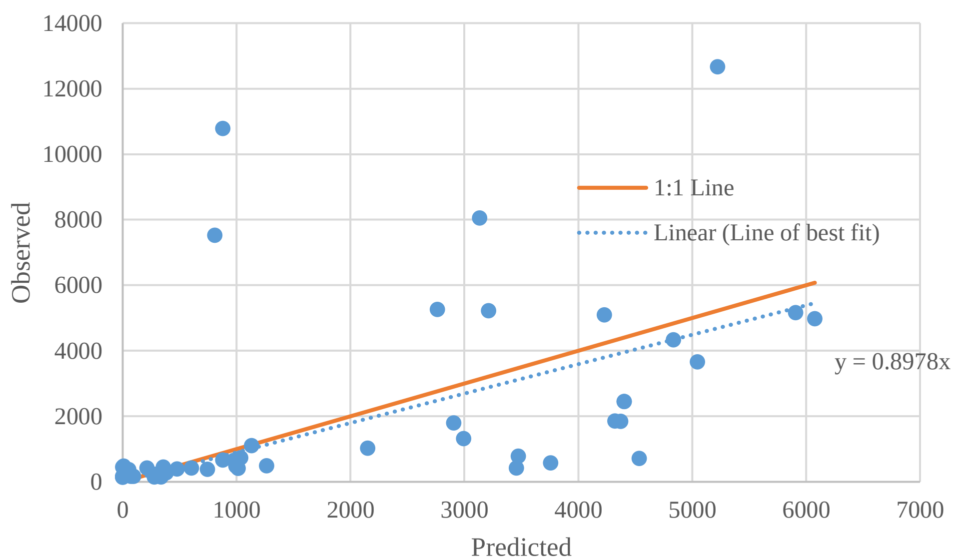

Figure 5-10- PM passenger car volumes

Since EMME's automated demand adjustments did not significantly improve the model, but made some unrealistic changes to the OD matrices, initial (i.e., unmodified) demand estimates were used for this research. Due to the large zonal aggregation scheme, intra-CD flows are absent from model, which is likely responsible for a large part of the difference in observed and predicted car counts, especially on Highway 401. In sum, the model represents travel times and truck flows well, but passenger flows would benefit from further calibration. For the purposes of preliminary research, the model is a good representation of Ontario's highway freight flows, and can be used for a preliminary assessment of trade criticality, especially in relative terms. Ongoing and future work to improve this model is noted in the concluding chapter.

6. Ontario’s highway criticality case study

In this chapter, trade criticality and the Network Robustness Index (NRI) are determined for the Ontario highway network, and compared with truck volumes, as means of identifying critical highway segments.

6.1. Trade Criticality

Figure 6-1 shows the trade criticality of Ontario’s highways during the AM peak hour. Thicker and thinner bars illustrate the most critical and least critical highways in Figure 6-1, respectively. During the AM peak hour, sections of Highway 401 (officially named Mac Donald-Cartier Freeway) and Highway 400 have the most critical highway segments. The sections of Highway 401 which are most critical are located west of the GTA. These include: Mill St. to Norwich Ave. (with trade criticality of $1978); between Oxford Road 3 and Cedar Creek Rd. ($1850); from Oxford 2 to Drumbo Rd. ($1662); from Foldens Line to Mill St. ($1623); between Cedar Creek Rd. and Oxford Road 3 ($1605); and from Drumbo Rd. to Oxford 2 ($1568). There is also unsatisfied demand (i.e., disconnected OD pairs) when two segments of Highway 401 are removed (from East Puce Rd. to Manning Rd. and vice-versa) in Lakeshore Ontario. The section of Highway 400 which is most critical is from Rankin Lake Rd. to J. R. Drive ($2546) in the town of Parry Sound.

There are 14 critical border crossings comprising highways and bridges to external zones, which result in unsatisfied demand as a result of their closure. Six of these critical border crossings are to Quebec: two of them are Autoroute 20 (Autoroute du Souvenir) in both directions, two of them are Autoroute 40 (Autoroute Felix-Lecierc) in both directions, and the last two are MacDonald Cartier Bridge in both directions. The other eight critical border crossings are with the United States (US), including through Blue Water Bridge (Highway 402) in Sarnia, the Queenston-Lewiston Bridge in Niagara Falls, the Thousand Island International Bridge near Kingston, and the Peace Bridge in Fort Erie, which are all critical in both directions.

Figure 6-1- Trade criticality of Ontario's highway infrastructure during the AM peak. IDs of most critical segments are listed in Table 6-1

Figure 6-2 shows the trade criticality of Ontario's highway infrastructure during PM peak hour. As in Figure 6-2, thicker and thinner bars illustrate the most critical and least critical highways, respectively. Notably, some of the most critical highway segments including those resulting in unsatisfied demand during the AM peak and PM peak are the same. The results suggest that a number of segments on Highway 401 located west of the GTA are highly critical. These include: Oxford Rd. 3 to Cedar Creek Rd. (with trade criticality of $2172), from Oxford 2 to Drumbo Rd. ($2008), from Northumberland St. to Cedar Creek Rd. ($1917), from Mill St. to Norwich Ave. ($1907), from Highbury Ave. South to Veterans Memorial Pkwy ($1826), from Foldens Line to Mill St. ($1821), and from Westchester Bourne to Dorchester Rd. ($1806). There are also unsatisfied demands when three segments of Highway 401 are removed: from Concession Rd. 11 to Provincial Rd., from Manning Rd. to Concession Rd. 11, and from East Puce Rd. to Manning Rd., all in Lakeshore Ontario.

There are 16 critical border crossings resulting in unsatisfied demand during the PM peak, 8 of which are to Quebec: Autoroute 20 (Autoroute du Souvenir), Trans-Canada Highway, Autoroute 40 (Autoroute Felix-Lecierc) and MacDonald Cartier Bridge, all in both directions. The other eight critical border crossings are with the USA, including through Blue Water Bridge (Highway 402) in Sarnia, the Queenston-Lewiston Bridge in Niagara Falls, the Thousand Island International Bridge near Kingston, and Peace Bridge in Fort Erie, all of which are critical in both directions.

Figure 6-2- Trade criticality of Ontario's highway infrastructure during the PM peak. IDs of most critical segments are listed in Table 6-2

Figure 6-3 shows the number of links and cumulative percentages of trade criticality values for the AM and PM peak hours. In this application, the number of links in the network that have a trade criticality within a specified range is represented. For example, 971 links have a trade criticality between $1 and $99 in the PM peak (tallest bar on Figure 6-3). Recall that the trade criticality of a link represents the increase in the cost of delays to all shipments in the network as a consequence of closing the link. Trade criticalities generally range from $0-$2999. As illustrated in Figure 6-3, the histogram of trade criticalities for the Ontario highway network resembles a Gamma distribution for both AM and PM peak hours. The maximum number of links of trade criticality for the two periods are between $1 and $99 with frequencies of 634 and 971, respectively. Combining these least critical segments with segments having a trade criticality of zero, results in 44% and 54% of the highway network in the AM and PM peak hours, respectively, having a trade criticality of less than $100 (i.e., no or low criticality). As trade criticality increases, the frequency of occurrence decreases. For example, segments within the range of $900 to $999 have frequencies of 50 and 42 for the AM peak and PM peak hour, respectively.

There are also cases where trade criticality is negative or where the highway closure results in unsatisfied demand. Thirty-one links, representing 1.02% of total highway links in the network, result in unsatisfied demand for both the AM and PM peaks. 266 and 281 links result in a negative trade criticality value for the AM and PM peak hours respectively (representing 8.76% and 9.26% of total highway links). These links indicate the network is better off as a result of their removal. In a real-world terms, this means that the removal of the link did not result in shipment delay costs, but rather shipment time improvements resulting in cost savings. Braess's Paradox states that adding a new road to a congested traffic network can increase the network-wide total travel time, and hence the removal of an existing road can decrease the network-wide total travel time. Similarly, it is seen in these cases that trade criticality is negative by removing these links. These cases represent either Braess's Paradox (network-wide total travel times decrease), or cases where high-value trucks benefit at the expense of low-value trucks (since travel times are additionally weighted by the value of goods in Equation 2 and 3).

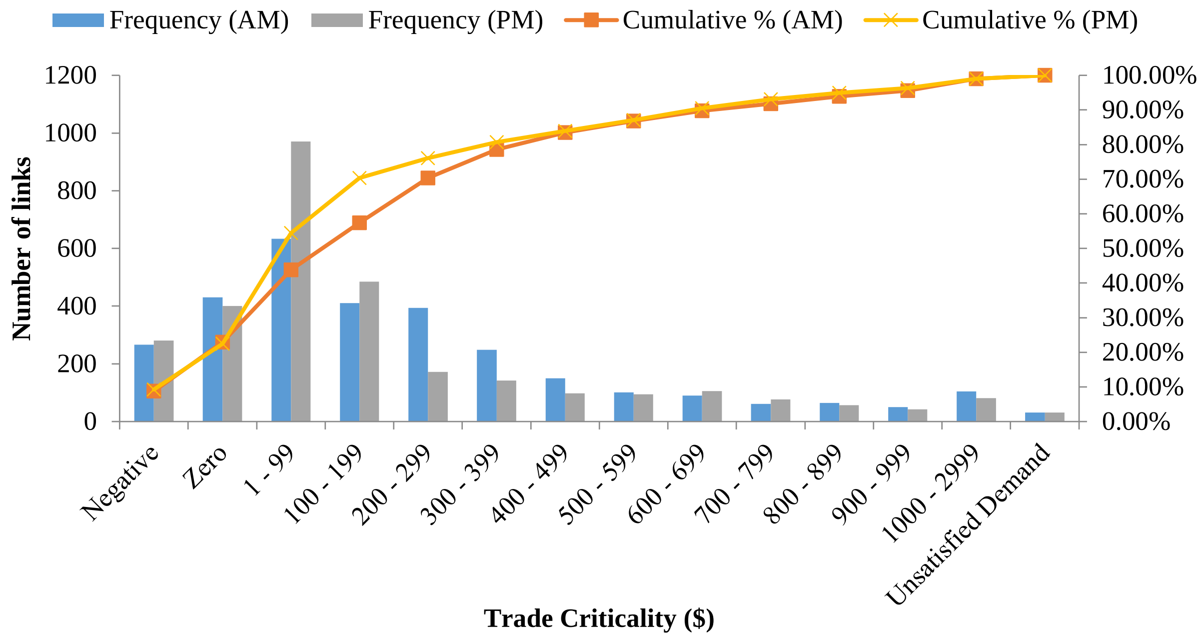

Figure 6-3- Frequency-distribution plot of trade criticality in the Ontario highway network.

6.2. The Network Robustness Index

During the AM peak hour, sections of Highway 401 (officially named Mac Donald-Cartier Freeway) and Highway QEW have the most critical highway segments. The sections of Highway 401 which are most critical are located west of the GTA. These include: E Puce Rd to Manning Rd (with NRI of 23698938 veh.min), Mill St. to Norwich Ave. (23679114 veh.min); between Highway 25 and Steeles Ave E (23678926 veh.min), from Drumbo Rd to highway 2 (23678811 veh.min), between Highway Ave S and Pond Mills Rd (23791673 veh.min), from Cedar Creek Rd to Highway 3 (23678457 veh.min). The sections of Highway QEW which are most critical is from Ontario St to Bartlet Rd N (23678477 veh.min) and between Millen Rd and Glover Rd (23678460 veh.min).

During the PM peak hour, sections of Highway 401 are the most critical highway segments. Notably, some of the most critical highway segments including those resulting in unsatisfied demand during the AM peak and PM peak are the same. The results suggest that a number of segments on Highway 401 located west of the GTA are highly critical. These include: from E Puce

Rd to Manning Rd (with NRI of 23709369 veh.min), between Lakeshore Rd 111 and Lakeshore Rd 107 (23680506 veh.min), from Belle River Rd to E Puce Rd (23680421 veh.min), between Cedar Creek Rd and Highway 3 (23679990 veh.min), from Drumbo Rd to highway 2 (23679868 veh.min), from Fountain St S to Cedar Creek Rd (23679668 veh.min), between Drumbo Rd and Cedar Creek Rd (23679451 veh.min) and from Mill St to Norwich Ave (23679415 veh.min).

Note that in the Network Robustness Index, truck volume and passenger car volume are considered, whereas in trade criticality only considers truck volumes since only cargo value delays are measured. Notably, the amounts for critical links in NRI are close to one another.

During AM and PM peak hours, there are some border crossings (similar to trade criticality) comprising highways and bridges to external zones, which result in unsatisfied demand as a result of their closure.

6.3. Truck Volumes

Figure 6-4 and Figure 6-5 show the modelled AM and PM truck volumes, respectively. In the AM peak hour, the highway segments carrying the highest truck volumes are found in two clusters along Highway 401: 1) through Pickering, Ajax, and Whitby; and 2) between London and Woodstock. In the PM peak hour, the highways segments carrying the highest truck volumes are found clustered between London and Woodstock. Note that the high truck volumes in the AM peak hour through Pickering, Ajax, and Whitby, did not result in the highest trade criticalities. The network redundancy in Pickering, Ajax, and Whitby through the Highway 407, Highway 7, and Kingston Rd. provides ample alternatives for re-routing, which will naturally reduce the associated delays experienced by trucks and ultimately reduce the criticality of Highway 401 through this area.

Although the high truck volumes between London and Woodstock resulted in links with high trade criticality, highway segments between Woodstock and Cambridge also have high trade criticality despite their lower truck volumes. The lack of network redundancy surrounding Highway 401 between Woodstock and Cambridge will naturally increase its criticality due to the lack of suitable alternatives for re-routing.

Overall, there is a large amount of truck movements in the GTA, but the high degree of network redundancy results in lower trade criticality values. Hence, concentrations of trucks are not necessarily critical if there is a corresponding concentration of network redundancy.

Figure 6-4- AM Truck Volumes. IDs of Highest Volumes are listed in Table 6-3. * represents IDs 1-3, 5, 7-8.

Figure 6-5- PM Truck Volumes. IDs of Highest Volumes are listed in Table 6-4- * represents IDs 1-10.

6.4. Comparison

Table 6-1 to Table 6-6 show the comparison of top ranked highway segments by trade criticality and corresponding rank in truck volume and network robustness index and vice-versa, for the AM and PM peak hours. Many of the most critical highway segments by trade criticality and network robustness index are on Highway 401 in locations west of the GTA near Woodstock, Ayr, Brant, and Beachville. On the other hand, many of the most critical highway segments by truck volume are on Highway 401 in locations east of the GTA near Ajax, Whitby, Putnam, and Oshawa.

Overall, the correlation coefficients of the most critical highway segments by trade criticality ranking and corresponding ranking for truck volume for the AM and PM peak hours are 0.55 and 0.59, respectively. The correlation coefficients of the most critical highway segments by trade criticality ranking and corresponding ranking for NRI for the AM and PM peak hours are 0.93 and 0.92, respectively. The correlation coefficients of the most critical highway segments by network robustness index ranking and corresponding ranking for truck volume for the AM and PM peak hours are 0.51 and 0.61, respectively. The value of the correlation coefficient for the AM and PM peak hours shows the ranking based on trade criticality or ranking based on NRI has correlation with corresponding ranking by truck volume, but the measures are not perfectly correlated as trade criticality additionally considers the truck's value of goods and the surrounding highway network characteristics. The value of correlation coefficient for AM and PM peak hour shows the ranking based on trade criticality has the best correlation with corresponding ranking by NRI. Note that these correlations are specific to Ontario, and could vary dramatically depending on the passenger demands, freight demands, and network topography of a particular area.

Comparisons can also be made to the value of goods by highway segment (Figure C.1 in Appendix C), or the Average Annual Daily Traffic (AADT) (Figure C.2 in Appendix C), which have patterns quite similar to truck volumes (Figure 6-4 and Figure 6-5).

Table 6-1- Comparison of Top Ranked Highway Segments by Trade Criticality (AM)

Highway segment	Node i	Node j	Trade Criticality ($)	Trade Criticality Rank	Truck Volume Rank	NRI Rank
401 from E Puce Rd to Manning Rd	14210	14217	10533	1	281	1
401 from E Puce Rd to Manning Rd	14222	14210	10304	2	282	2
400 from Rankin Lake Rd to JR Dr	2418	2401	2546	3	2294	28
401 from Mill St to Norwich Ave	12086	12082	1978	4	152	3
401 from Mill St to Norwich Ave	12095	12091	1978	5	154	4
401 from highway 3 to Cedar Creek Rd	11058	10633	1850	6	294	45
401 from highway 2 to Drumbo Rd	11324	11056	1662	7	296	91
401 from Foldens Line to Mill St	12307	12137	1623	8	86	16
401 from Cedar Creek Rd to Highway 3	10631	10806	1605	9	163	10
401 from Drumbo Rd to highway 2	11023	11320	1568	10	165	6

Table 6-2- Comparison of Top Ranked Highway Segments by Trade Criticality (PM)

Highway segment	Node i	Node j	Trade Criticality ($)	Trade Criticality Rank	Truck Volume Rank	NRI Rank
401 from E Puce Rd to Manning Rd	14222	14210	13125	1	339	1
401 from E Puce Rd to Manning Rd	14210	14217	12891	2	338	2
401 from highway 3 to Cedar Creek Rd	11058	10633	2172	3	93	8
401 from highway 2 to Drumbo Rd	11324	11056	2008	4	94	19
401 from Nothumberland St to Cedar Creek Rd	10633	10624	1917	5	96	28
401 from Mill St to Norwich Ave	12086	12082	1907	6	23	9
401 from Mill St to Norwich Ave	12095	12091	1907	7	25	10
401 from Highbury Ave South to Veterans Memorial Pkwy	13059	13054	1826	8	27	51
401 from Foldens Line to Mill St	12307	12137	1821	9	6	12
401 from Westchester Bourne to Derchester Rd	13031	13000	1806	10	17	35

Table 6-3- Comparison of Top Ranked Highway Segments by Truck Volume (AM)

Highway segment	Node i	Node j	Truck Volume (veh/hr)	Truck Volume Rank	Trade Criticality Rank	NRI Rank
401 from Brock Rd to Westney Rd South	6268	6238	354	1	120	54
401 from Brock st South to Thickson Rd	6129	6098	352	2	133	204
401 from Brock st South to Thickson Rd	6140	6129	352	3	236	264
401 from Westney Rd to SouthBrock Rd	6211	6140	352	4	179	219
401 from Church St to Harwood Ave South	6238	6211	352	5	209	108
401 from Towerline Rd to Norwich Ave	11990	12013	349	6	115	61
401 from Thickson Rd to Stevenson Rd South	6087	6058	347	7	374	602
401 from Brock st South to Stevenson Rd South	6098	6087	347	8	312	614
401 from Putnam Rd to Elgin Rd	12876	12896	345	9	328	619
401 from Putnam Rd to Elgin Rd	12896	12935	345	10	422	822

Table 6-4- Comparison of Top Ranked Highway Segments by Truck Volume (PM)

Highway segment	Node i	Node j	Truck Volume (veh/hr)	Truck Volume Rank	Trade Criticality Rank	NRI Rank
401 from Elgin Rd to Putnam Rd	12897	12879	318	1	35	44
401 from Culloden Line to Harris St	12460	12458	317	2	62	245
401 from Putnam Rd to Culloden Line	12514	12460	317	3	88	304
401 from Putnam Rd to Culloden Line	12518	12514	317	4	64	230
401 from Elgin Rd to Putnam Rd	12879	12518	317	5	180	398
401 from Foldens Line to Sweaburg Rd	12307	12137	317	6	9	12
401 from Plank Line to Foldens Line	12336	12307	317	7	28	146
401 from Plank Line to Foldens Line	12352	12336	317	8	17	43
401 from Plank Line to Foldens Line	12437	12352	317	9	130	345
401 from Plank Line to Foldens Line	12447	12437	317	10	53	136

Table 6-5- Comparison of Top Ranked Highway Segments by Network Robustness Index (AM)

Highway segment	i	j	NRI (veh.min)	NRI Rank	Trade Criticality Rank	Truck Volume Rank
401 from E Puce Rd to Manning Rd	14210	14217	23698938	1	1	281
401 from E Puce Rd to Manning Rd	14222	14210	23698510	2	2	282
401 from Mill St to Norwich Ave	12086	12082	23679114	3	4	152
401 from Mill St to Norwich Ave	12095	12091	23679114	4	5	154
401 from Highway 25 to Steeles Ave E	9436	9352	23678926	5	28	559
401 from Drumbo Rd to highway 2	11023	11320	23678811	6	10	165
401 from Highway Ave S to Pond Mills Rd	13100	13106	23678632	7	15	170
QEW from Ontario St to Bartlet Rd N	11428	11432	23678477	8	63	60
QEW from Millen Rd to Glover Rd	10944	11027	23678460	9	128	159
401 from Cedar Creek Rd to Highway 3	10631	10806	23678457	10	9	163

Table 6-6- Comparison of Top Ranked Highway Segments by Network Robustness Index (PM)

Highway segment	i	j	NRI (veh.min)	NRI Rank	Trade Criticality Rank	Truck Volume Rank
401 from E Puce Rd to Manning Rd	14222	14210	23709369	1	1	339
401 from E Puce Rd to Manning Rd	14210	14217	23708501	2	2	338
401 from Lakeshore Rd 111 to Lakeshore Rd 107	14224	14222	23680506	3	20	340
401 from Belle River Rd to E Puce Rd	14232	14224	23680421	4	23	341
401 from Cedar Creek Rd to Highway 3	10631	10806	23679990	5	31	198
401 from Drumbo Rd to highway 2	11023	11320	23679868	6	40	201
401 from Fountain St S to Cedar Creek Rd	10358	10628	23679668	7	44	262
401 from Drumbo Rd to Cedar Creek Rd	11058	10633	23679451	8	3	93
401 from Mill St to Norwich Ave	12086	12082	23679415	9	6	23
401 from Mill St to Norwich Ave	12095	12091	23679415	10	7	25

6.5. Discussion

Results in the preceding section point to a number of key findings. First, trade criticality has some correlation with truck volume, but differs by considering the values of shipments and the physical redundancy in the network (Table 6-1to Table 6-6). For this reason, areas with high truck volumes are not necessarily critical. For example, due to the high redundancy of the highway network within the GTA, highways become more critical further away (Figure 6-1 and Figure 6-2). Moreover, sections of Highway 401 located west of the GTA are more critical than those located east of the GTA because of the lower redundancy in the western portion of the network, despite carrying lower truck volumes. Second, trade criticalities are widely distributed and resemble a gamma distribution, with approximately half of the Ontario highway network being non-critical (trade criticality of zero) or having very low criticality (less than $100). As the magnitude of trade criticality increases, the frequency of occurrence decreases (Figure 6-3). Therefore, efforts aimed at improving the resiliency of the Ontario highway network can focus on the Most Critical Links (MCLs), of which there are few: 2.67% with a trade criticality greater than $1000 and 1.02% that result in unsatisfied demand (Figure 6-3). Note that segments resulting in unsatisfied demand are the result of boundary effects of the model (where external zones are connected by only one highway segment), but nonetheless represent critical borders for Ontario's imports and exports that lack nearby redundancy. Finally, trade criticality varies by time of day (compare Figure 6-1 and Figure 6-2, or review Table 6-1 to Table 6-6), and therefore the timing of closures plays a large role in the associated costs. Hence, for real-world closures that may last multiple hours or days, a more comprehensive trade criticality measure should be computed by summing the results of specific hourly traffic assignments, rather than generalizing the results of a one hour assignment to other time periods.

6.5.1. Value of work

Measuring the trade criticality of transportation networks and identifying the MCLs has many practical implications. First and foremost, this measure is tailored for freight transportation planning. For example, physical redundancy can be planned for the MCLs to reduce overall economic vulnerability. Design efforts can be focused towards reducing the likelihood and consequence of disruptions or closures on these links. And as Hummels (Hummels, D. L., 2012) notes, with value of time saved, one can then calculate the monetary benefits of these initiatives (transportation improvements in this context) and how they compare to the costs incurred (i.e., cost-benefit analysis). Second, this measure can be used for highway maintenance and operations. Maintenance and reconstruction efforts can be coordinated to avoid scenarios involving combinations of links that have high criticality. Prioritization for road maintenance and repair should also consider economic criticality, including winter road maintenance programs. MCLs could also be considered for greater surveillance through more highway patrols by policing organizations. These examples demonstrate the many practical applications of determining the trade criticality of highway infrastructure.

6.5.2. Limitations

One of the limitations of the results determined in this research is that commodity *types* are not considered, only commodity *values*. In other words, it is assumed that each day in transit is worth 2.1 percent of the value of the good, as determined by econometric estimates in Hummels et al. (Hummels, D. L., 2012). However, the study from where the value of time (α) is taken also finds substantially higher time values for automotive goods (4.3 percent) and for foods and beverages (3.1 percent). These results are sensible in the contexts of just-in-time manufacturing and spoilage, respectively. However, due to the reduced number of observations used to estimate these coefficients, it is unclear whether coefficient heterogeneity reflects true variation or noise. As such, further investigation into the heterogeneity of the value of time by commodity would be useful. Another limitation is that these results exclude the additional operating costs incurred by carriers due to rerouting (e.g., fuel costs). However, these costs can easily be added to trade criticality if desired by taking into account the increase in route distances and travel times and the corresponding costs per units of travel. Remaining limitations of the results stem from the newly-developed Ontario highway network model. Correlation coefficients (discussed in the section 5.4) indicate the model is a good representation of truck trips throughout Ontario, with fairly accurate travel times. But congestion effects (incorporated into trade criticality through delays) could be improved further by refining passenger demand estimates, especially those using Highway 401. Research is currently underway to improve passenger demand estimates by: including intra-CD trips in the traffic assignment, including external-external passenger trips; and ensuring long-distance passenger trips are gravitating towards highways (i.e., not “rat-running” throughout the network).

7. Conclusion

Events that disable parts of the highway transportation network may affect travel times and ultimately threaten economic productivity. While previous studies of criticality typically focus on the impacts of natural disasters or terrorist attacks on system-wide travel times, they have not quantified the costs associated with disruptions to the economy via the freight transportation system. This research quantified the economic criticality of Ontario's highway infrastructure using a new measure of criticality that determines the cost of highway closures in dollar values ($) based on the value of goods, the time delayed, and the associated value of time and compared the results of trade criticality with two other measures (truck volume and network robustness index) as a case study. This measure, trade criticality, reflects a short-term economic criticality or trade criticality, since it captures the immediate costs of shipment delays, all else being equal. This measure differs theoretically from previous criticality measures (revisit Figure 3-1) and provides new insights to critical freight infrastructure, as demonstrated by examining provincial highways in Ontario. This measure has many potential applications in freight transportation planning, operations and maintenance.

As discussed in Chapter 6, trade criticality and network robustness index are correlated together but the results for correlation coefficients of the most critical highway segments by trade criticality or by NRI ranking and corresponding ranking for truck volume are lower than the other two measures. In other words, by considering only volume, the criticality of a highway segment cannot be accurately measured. An advantage of trade criticality compared to NRI, is that the measure results in dollar values ($), and hence one can then calculate the monetary benefits of potential transportation improvements for comparison (i.e., cost-benefit analysis).

7.1. Future work

This research leaves ample room for future work in transportation research including three directions which are largely unexplored to date. First, only networks with a single mode (automobile/truck) have been considered thus far. Extending trade criticality to look at other modes, such as rail, and key trade infrastructure, such as ports and intermodal facilities, would be useful to gain a more comprehensive understanding of trade criticality. Second, the interdiction of links in isolation have been studied. However, real-world transportation networks may have multiple links disrupted or closed at the same time due to various circumstances (e.g., incidents, construction operations, extreme weather events, etc.). Moreover, the combined impact of interdicting two links is not simply the sum of their impacts when interdicted individually (reconsider Figure3.1). A complete theoretical analysis of transportation network criticality might consider interdicting all elements in the power set of links: that is, the set of all subsets of links in the network. Third, short term impacts of link interdictions (e.g., increases in travel costs) have been studied, but the long-term economic criticality of infrastructure differs because of longer-term decisions (such as firm and household location choices). Extending trade criticality, which we suggest represents a short-term economic criticality, to a longer-term measure, which includes land use and economic impacts (e.g., through a Computable General Equilibrium (CGE) model), would be useful in understanding another dimension of economic criticality. These and other directions would only expand the vast array of criticality applications discussed previously.

Finally, engaging various stakeholders such as shippers, carriers, and government agencies, in a discussion about criticality and prioritization is an area of future work that would benefit practical applications. For example, while prioritizing highway infrastructure by truck volumes may seem impartial, it may not be immediately clear why road segments with trucks carrying higher-value shipments (or more time sensitive commodities) are deemed more critical to the economy than road segments with trucks carrying lower-value shipments (or less time sensitive commodities). Public participation and stakeholder engagement are key ingredients to effective transportation planning.

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Appendix (A)

Appendix A: Hourly Truck Factors (Weekday)

Table A.1- Hourly truck factors (Weekday)

ZONE	WD_T_0	WD_T_1	WD_T_2	WD_T_3	WD_T_4	WD_T_5	WD_T_6	WD_T_7	WD_T_8	WD_T_9	WD_T_10	WD_T_11	WD_T_12	WD_T_13	WD_T_14	WD_T_15	WD_T_16	WD_T_17	WD_T_18	WD_T_19	WD_T_20	WD_T_21	WD_T_22	WD_T_23
1	0.03237	0.03102	0.02741	0.02447	0.02254	0.02526	0.03223	0.03846	0.04104	0.04267	0.04145	0.04093	0.04451	0.04836	0.05407	0.05752	0.05967	0.05859	0.05074	0.04618	0.04599	0.04856	0.04610	0.03986
2	0.02907	0.02636	0.02458	0.02430	0.02540	0.02871	0.03173	0.03649	0.04359	0.05071	0.05112	0.05335	0.05296	0.05432	0.05399	0.05427	0.05096	0.05155	0.04791	0.04805	0.04281	0.04322	0.03980	0.03474
3	0.01847	0.01682	0.01613	0.01773	0.02378	0.03980	0.04886	0.04330	0.05191	0.06563	0.06931	0.07134	0.07060	0.06806	0.06430	0.05476	0.04194	0.03595	0.03789	0.03505	0.03149	0.02834	0.02615	0.02240
4	0.02418	0.02200	0.02262	0.02513	0.02750	0.03099	0.03779	0.04188	0.04732	0.05028	0.05453	0.05833	0.05849	0.05776	0.05781	0.05597	0.05073	0.04719	0.04372	0.04210	0.04185	0.03817	0.03404	0.02963
5	0.00592	0.00592	0.00790	0.01185	0.01712	0.02567	0.04016	0.08427	0.09151	0.08690	0.06517	0.07176	0.06320	0.07110	0.06122	0.06781	0.07242	0.04806	0.03094	0.01975	0.02041	0.01251	0.01119	0.00724
6	0.01948	0.01873	0.01648	0.01236	0.02547	0.04120	0.04869	0.06180	0.05768	0.06442	0.06030	0.06442	0.07154	0.06442	0.06929	0.05805	0.05243	0.04232	0.03745	0.02996	0.02397	0.02322	0.02022	0.01610
7	0.00875	0.00693	0.00784	0.01258	0.01895	0.02533	0.03900	0.05358	0.06944	0.06360	0.07399	0.08001	0.07983	0.07162	0.06962	0.06761	0.05941	0.05176	0.03900	0.03025	0.02132	0.02588	0.01349	0.01021
8	0.00813	0.00583	0.00602	0.00641	0.01181	0.02926	0.06813	0.07287	0.07449	0.06488	0.06024	0.05647	0.05484	0.06130	0.07081	0.06072	0.05279	0.05455	0.04781	0.03514	0.03117	0.02768	0.02348	0.01516
9	0.01656	0.01163	0.01340	0.01794	0.01814	0.02858	0.03864	0.04829	0.06406	0.05381	0.05204	0.06347	0.05894	0.06308	0.06032	0.06505	0.06406	0.04889	0.05086	0.04613	0.03903	0.03154	0.02563	0.01991

10	0.01431	0.01465	0.01297	0.01791	0.02251	0.03465	0.05390	0.05800	0.06127	0.06512	0.06486	0.06118	0.06327	0.06252	0.06645	0.05993	0.05499	0.04720	0.03490	0.03164	0.03256	0.02636	0.02017	0.01866
11	0.00873	0.00764	0.00436	0.00818	0.02073	0.03983	0.04528	0.06983	0.06819	0.06438	0.07038	0.07965	0.07474	0.07420	0.06710	0.06383	0.05292	0.05019	0.03764	0.02946	0.02346	0.01637	0.01037	0.01255
12	0.02328	0.03659	0.03465	0.02688	0.03326	0.03714	0.04296	0.03548	0.04102	0.04518	0.05377	0.04573	0.05183	0.05599	0.05127	0.05876	0.05017	0.03659	0.04850	0.05072	0.04351	0.03076	0.03271	0.03326
13	0.01249	0.01145	0.01187	0.01159	0.01711	0.03067	0.04676	0.05551	0.05838	0.06660	0.06980	0.07044	0.06952	0.07080	0.07013	0.06117	0.05489	0.04769	0.04179	0.03401	0.02927	0.02320	0.01910	0.01576
14	0.02261	0.02467	0.02107	0.01850	0.02004	0.03803	0.04419	0.04368	0.04933	0.05653	0.06115	0.05704	0.06680	0.06578	0.05858	0.06989	0.05550	0.04162	0.03751	0.03649	0.03905	0.02929	0.02518	0.01747
15	0.00694	0.00893	0.00992	0.01885	0.02480	0.02480	0.05060	0.07044	0.06052	0.06944	0.06845	0.06448	0.05556	0.05952	0.05258	0.08433	0.05456	0.03968	0.03671	0.03075	0.02381	0.04464	0.01885	0.02083
16	0.01354	0.01103	0.01092	0.01229	0.00990	0.02184	0.03902	0.05995	0.06746	0.06279	0.05824	0.06018	0.06188	0.05881	0.06586	0.08156	0.07576	0.07189	0.04687	0.02639	0.02662	0.02264	0.01888	0.01570
17	0.02328	0.03659	0.03465	0.02688	0.03326	0.03714	0.04296	0.03548	0.04102	0.04518	0.05377	0.04573	0.05183	0.05599	0.05127	0.05876	0.05017	0.03659	0.04850	0.05072	0.04351	0.03076	0.03271	0.03326
18	0.01992	0.01894	0.01724	0.01415	0.02331	0.03180	0.05044	0.05417	0.05104	0.05448	0.06179	0.06017	0.05821	0.05749	0.05976	0.05783	0.05591	0.05119	0.04874	0.04131	0.03407	0.02777	0.02516	0.02509
19	0.00455	0.00303	0.00303	0.02121	0.02273	0.03636	0.05303	0.10303	0.06364	0.07424	0.07424	0.07424	0.06061	0.06515	0.06212	0.07727	0.05606	0.04091	0.02576	0.02273	0.01515	0.02273	0.01212	0.00606
20	0.01784	0.01558	0.01420	0.01403	0.02182	0.02926	0.03965	0.04589	0.05022	0.05905	0.06355	0.06580	0.06303	0.05697	0.06615	0.05870	0.05697	0.04554	0.04797	0.04416	0.03550	0.03186	0.02926	0.02701

21	0.02703	0.02637	0.02827	0.02362	0.02009	0.02539	0.03246	0.04234	0.04725	0.04967	0.05196	0.05994	0.05726	0.05503	0.05418	0.05726	0.05425	0.05124	0.04581	0.04790	0.04044	0.03756	0.03422	0.03049
22	0.02418	0.02200	0.02262	0.02513	0.02750	0.03099	0.03779	0.04188	0.04732	0.05028	0.05453	0.05833	0.05849	0.05776	0.05781	0.05597	0.05073	0.04719	0.04372	0.04210	0.04185	0.03817	0.03404	0.02963
23	0.01596	0.01613	0.01373	0.01613	0.01527	0.02316	0.03260	0.04135	0.04701	0.05165	0.06572	0.06417	0.06881	0.06520	0.07189	0.06812	0.06074	0.05525	0.05679	0.03723	0.03552	0.03037	0.03089	0.01630
24	0.03101	0.02587	0.02351	0.02348	0.02697	0.02939	0.03314	0.03708	0.04294	0.05184	0.05196	0.05138	0.05322	0.05277	0.05218	0.05241	0.05502	0.04986	0.05009	0.04668	0.04356	0.04057	0.03986	0.03522
25	0.02857	0.02839	0.02306	0.02223	0.02737	0.03390	0.03472	0.03347	0.03863	0.04728	0.05175	0.05554	0.05624	0.05792	0.05804	0.05286	0.04714	0.04375	0.04378	0.04797	0.04930	0.04146	0.04077	0.03586
26	0.02921	0.01668	0.01253	0.00981	0.01069	0.01794	0.02490	0.02485	0.02812	0.03345	0.04581	0.05394	0.06228	0.06534	0.06756	0.06911	0.06710	0.05440	0.05629	0.05939	0.05424	0.05206	0.04619	0.03810
27	0.00798	0.00840	0.00966	0.01427	0.02981	0.03526	0.04282	0.05080	0.05961	0.07557	0.08018	0.07851	0.06843	0.07599	0.07053	0.06213	0.05751	0.05668	0.03065	0.02645	0.01721	0.01721	0.01092	0.01343
28	0.02703	0.02689	0.02490	0.02561	0.02731	0.03297	0.03580	0.04372	0.05080	0.05122	0.04556	0.05306	0.05321	0.05519	0.04882	0.05122	0.05193	0.05830	0.04910	0.04344	0.03764	0.03736	0.03424	0.03467
29	0.01835	0.02184	0.01741	0.02184	0.02437	0.02500	0.03671	0.07880	0.06519	0.05316	0.04873	0.05063	0.05190	0.05190	0.07278	0.05823	0.05538	0.05380	0.03449	0.03703	0.03671	0.02975	0.02722	0.02880
30	0.01279	0.01137	0.01184	0.00805	0.01563	0.02700	0.04263	0.05921	0.06490	0.06395	0.05874	0.06869	0.06916	0.07627	0.07958	0.07248	0.06679	0.05021	0.03884	0.03032	0.02653	0.01658	0.01611	0.01232
31	0.00694	0.00893	0.00992	0.01885	0.02480	0.02480	0.05060	0.07044	0.06052	0.06944	0.06845	0.06448	0.05556	0.05952	0.05258	0.08433	0.05456	0.03968	0.03671	0.03075	0.02381	0.04464	0.01885	0.02083

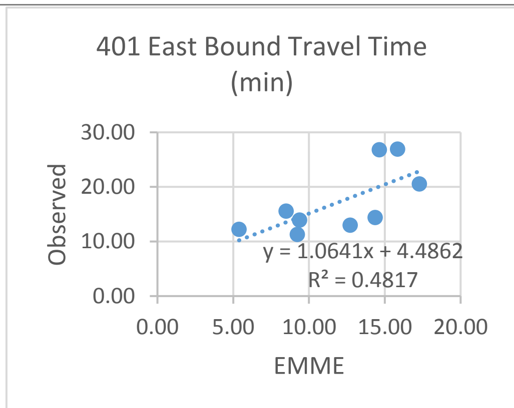
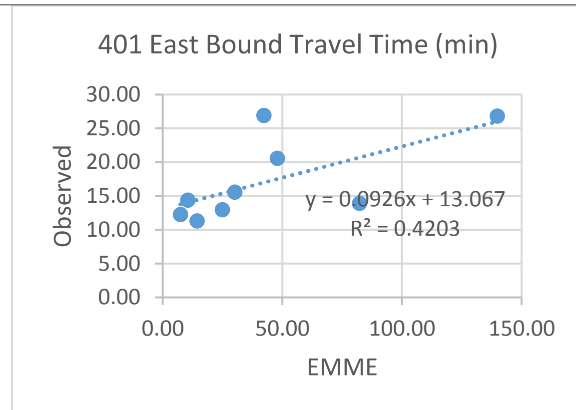
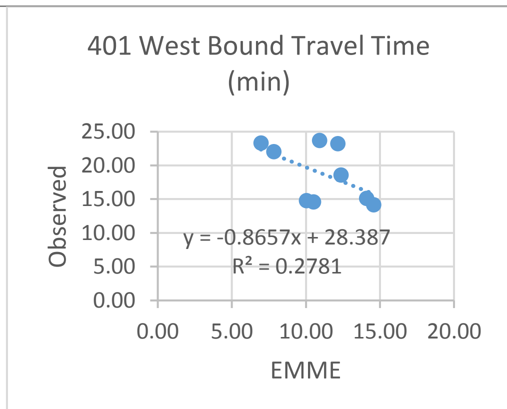
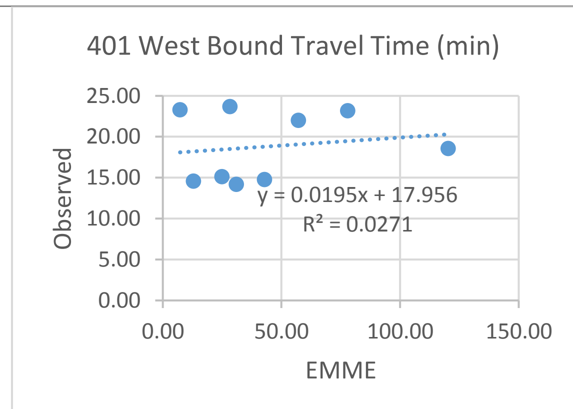
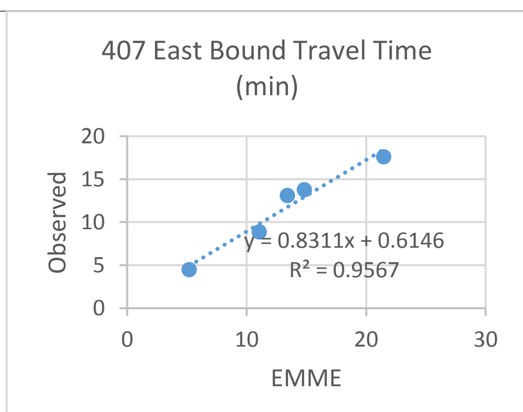
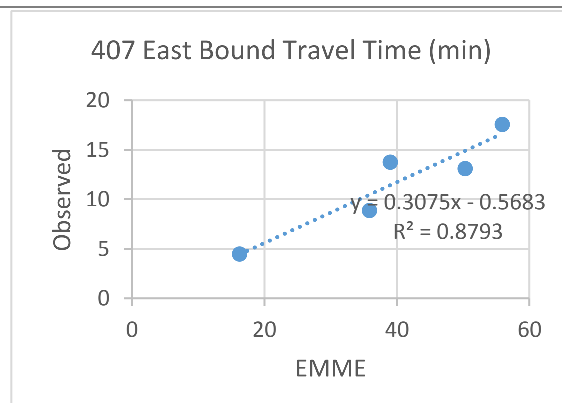
32	0.01229	0.00819	0.00737	0.00601	0.00983	0.02648	0.05788	0.08818	0.06798	0.07890	0.08408	0.07917	0.08436	0.08054	0.07071	0.06689	0.04559	0.03631	0.02457	0.01556	0.01556	0.01611	0.01010	0.00737
33	0.01962	0.01540	0.01338	0.01597	0.01921	0.02489	0.03445	0.04329	0.04564	0.05253	0.05674	0.06007	0.06266	0.06072	0.05991	0.05885	0.05950	0.05569	0.05188	0.04904	0.04272	0.03915	0.03243	0.02626
34	0.01266	0.00745	0.00596	0.01042	0.01415	0.02755	0.05659	0.06106	0.05733	0.09829	0.08637	0.09829	0.06031	0.05212	0.07446	0.06478	0.06180	0.03574	0.03276	0.02308	0.01564	0.01713	0.01042	0.01564
35	0.01835	0.02184	0.01741	0.02184	0.02437	0.02500	0.03671	0.07880	0.06519	0.05316	0.04873	0.05063	0.05190	0.05190	0.07278	0.05823	0.05538	0.05380	0.03449	0.03703	0.03671	0.02975	0.02722	0.02880
36	0.02187	0.01688	0.01528	0.01994	0.02653	0.03248	0.03859	0.04551	0.04599	0.05290	0.05531	0.05644	0.05998	0.05467	0.05403	0.05081	0.05435	0.05210	0.04969	0.04551	0.04502	0.04084	0.03538	0.02991
37	0.00798	0.00840	0.00966	0.01427	0.02981	0.03526	0.04282	0.05080	0.05961	0.07557	0.08018	0.07851	0.06843	0.07599	0.07053	0.06213	0.05751	0.05668	0.03065	0.02645	0.01721	0.01721	0.01092	0.01343
38	0.01279	0.01137	0.01184	0.00805	0.01563	0.02700	0.04263	0.05921	0.06490	0.06395	0.05874	0.06869	0.06916	0.07627	0.07958	0.07248	0.06679	0.05021	0.03884	0.03032	0.02653	0.01658	0.01611	0.01232
39	0.01596	0.01613	0.01373	0.01613	0.01527	0.02316	0.03260	0.04135	0.04701	0.05165	0.06572	0.06417	0.06881	0.06520	0.07189	0.06812	0.06074	0.05525	0.05679	0.03723	0.03552	0.03037	0.03089	0.01630
40	0.02251	0.01805	0.01692	0.01740	0.02141	0.03417	0.04754	0.03928	0.04069	0.06169	0.07129	0.07259	0.07139	0.06937	0.06268	0.04977	0.04072	0.03536	0.03910	0.04051	0.03653	0.03408	0.03052	0.02642
41	0.01948	0.01873	0.01648	0.01236	0.02547	0.04120	0.04869	0.06180	0.05768	0.06442	0.06030	0.06442	0.07154	0.06442	0.06929	0.05805	0.05243	0.04232	0.03745	0.02996	0.02397	0.02322	0.02022	0.01610
42	0.02660	0.02061	0.02024	0.02143	0.02583	0.03390	0.03724	0.04175	0.04566	0.05357	0.05841	0.05922	0.05909	0.05953	0.05969	0.05516	0.04900	0.04644	0.04340	0.04016	0.03750	0.03815	0.03590	0.03151

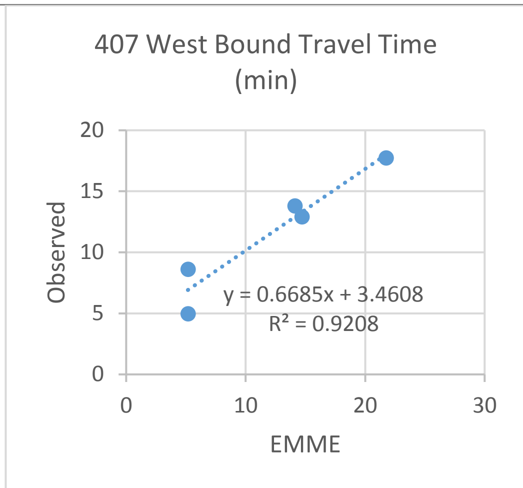
43	0.02703	0.02689	0.02490	0.02561	0.02731	0.03297	0.03580	0.04372	0.05080	0.05122	0.04556	0.05306	0.05321	0.05519	0.04882	0.05122	0.05193	0.05830	0.04910	0.04344	0.03764	0.03736	0.03424	0.03467
44	0.01385	0.01609	0.01341	0.02011	0.02257	0.02726	0.04067	0.08000	0.06950	0.05743	0.05676	0.05721	0.05453	0.05564	0.07061	0.06302	0.05810	0.05095	0.03352	0.03218	0.03263	0.02860	0.02302	0.02235
45	0.01354	0.01103	0.01092	0.01229	0.00990	0.02184	0.03902	0.05995	0.06746	0.06279	0.05824	0.06018	0.06188	0.05881	0.06586	0.08156	0.07576	0.07189	0.04687	0.02639	0.02662	0.02264	0.01888	0.01570
46	0.01229	0.00819	0.00737	0.00601	0.00983	0.02648	0.05788	0.08818	0.06798	0.07890	0.08408	0.07917	0.08436	0.08054	0.07071	0.06689	0.04559	0.03631	0.02457	0.01556	0.01556	0.01611	0.01010	0.00737
47	0.01632	0.01354	0.01207	0.01436	0.01517	0.02333	0.02904	0.03997	0.04781	0.05694	0.05776	0.06249	0.06347	0.06804	0.05939	0.06820	0.06347	0.05596	0.04764	0.05205	0.04291	0.03720	0.02872	0.02415
48	0.02936	0.02176	0.01965	0.01811	0.01896	0.02502	0.03027	0.04067	0.04844	0.04541	0.04735	0.05163	0.05089	0.05312	0.05249	0.05883	0.05643	0.05655	0.05472	0.04992	0.05043	0.04552	0.04067	0.03381
49	0.02240	0.01548	0.01336	0.01360	0.01572	0.01776	0.02599	0.04065	0.04261	0.05206	0.05360	0.06004	0.05906	0.06086	0.06232	0.06200	0.06314	0.06012	0.05629	0.04969	0.04456	0.04212	0.03373	0.03283

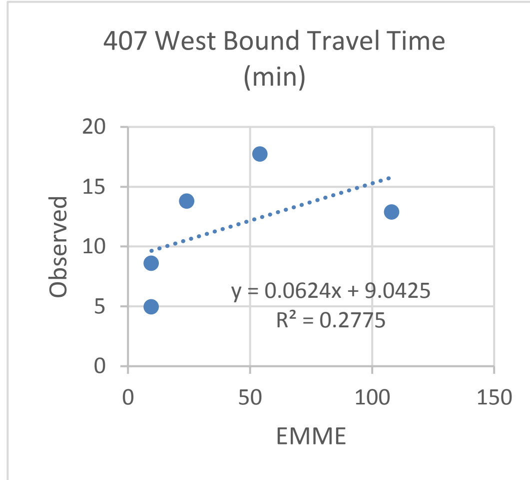
Appendix (B)

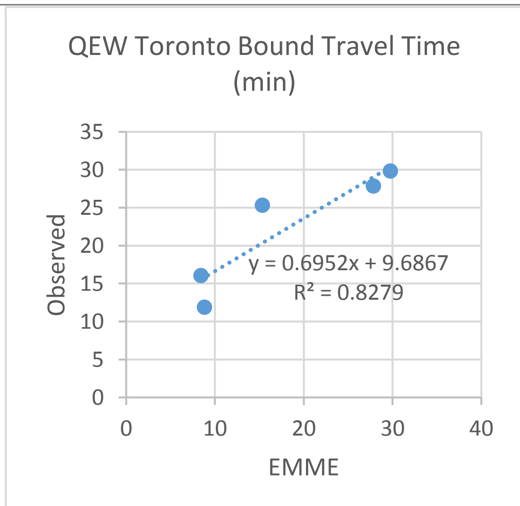
Appendix (B.1): Comparing the travel time before and after the adjustment (AM)

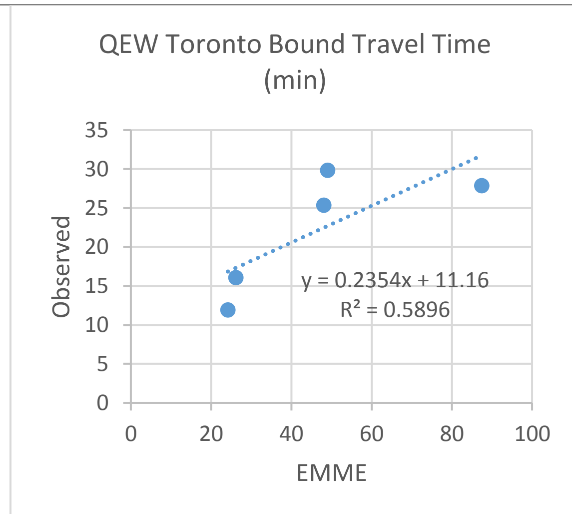
Table B.1- Comparing the travel time before and after the adjustment (AM)

8 am	Before Adjustment	After Adjustment
401		
		
407		

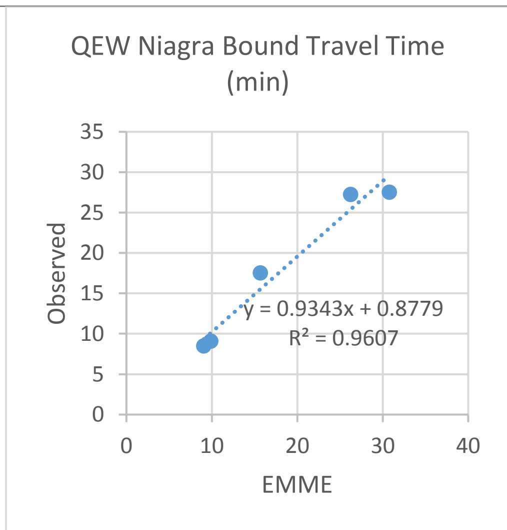

407 West Bound Travel Time (min)
Observed
EMME
y = 0.6685x + 3.4608
R² = 0.9208

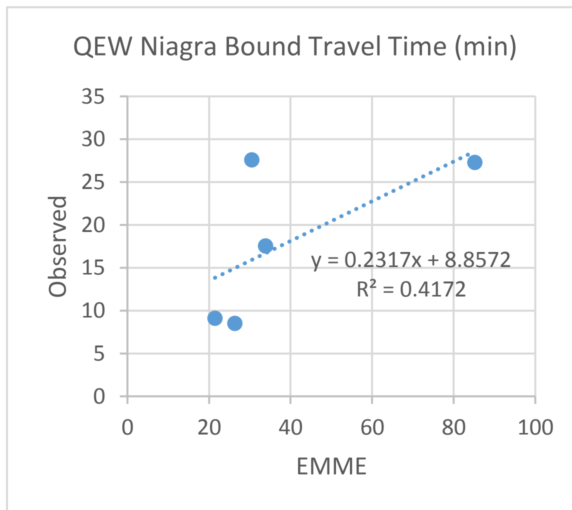

407 West Bound Travel Time (min)
Observed
EMME
y = 0.0624x + 9.0425
R² = 0.2775

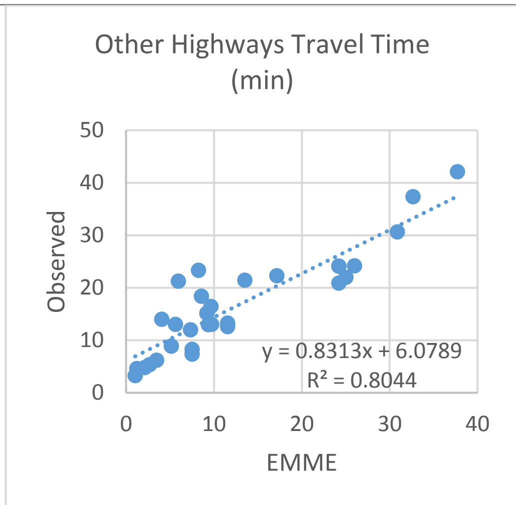
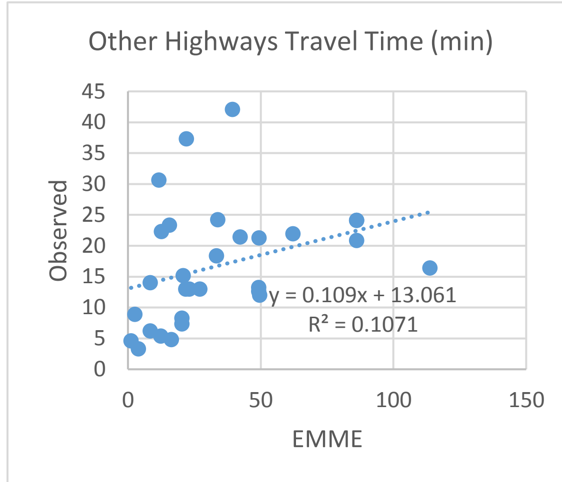
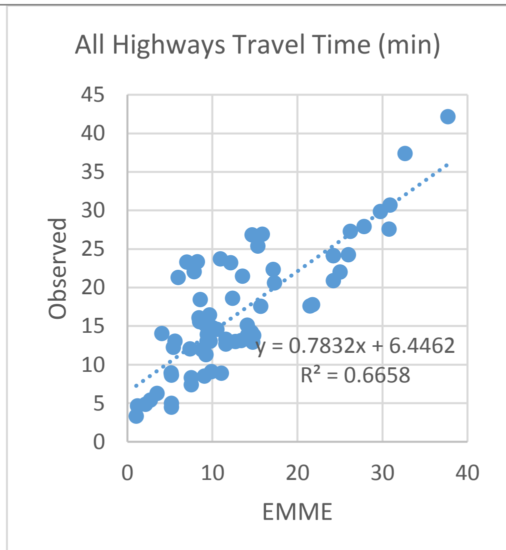
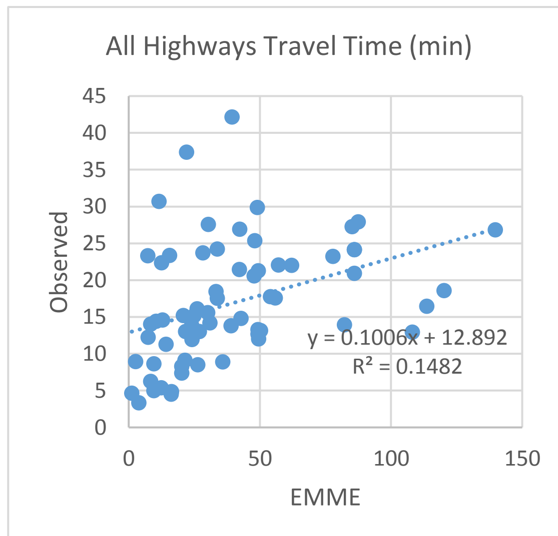

QEW Toronto Bound Travel Time (min)
Observed
EMME
y = 0.6952x + 9.6867
R² = 0.8279


QEW Toronto Bound Travel Time (min)
Observed
EMME
y = 0.2354x + 11.16
R² = 0.5896

QEW


QEW Niagra Bound Travel Time (min)
Observed
EMME
y = 0.9343x + 0.8779
R² = 0.9607


QEW Niagra Bound Travel Time (min)
Observed
EMME
y = 0.2317x + 8.8572
R² = 0.4172

Other		
All		

Other Highways Travel Time (min)
y = 0.8313x + 6.0789
R² = 0.8044
Observed
EMME

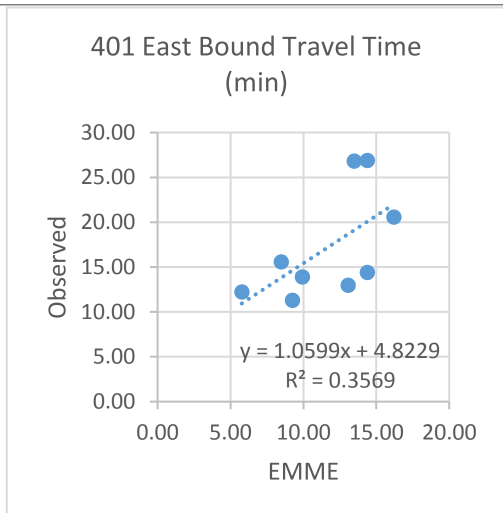
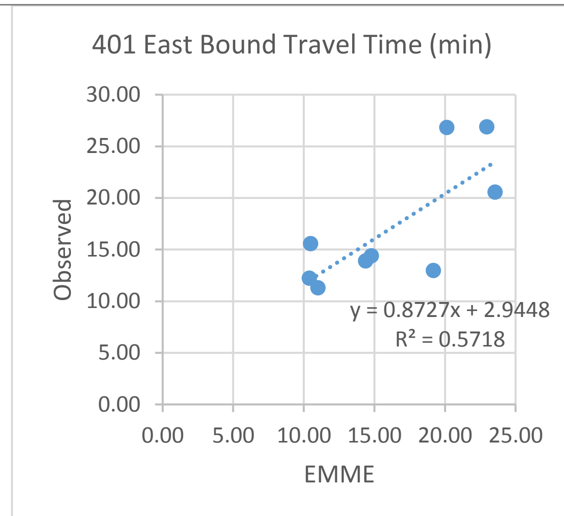
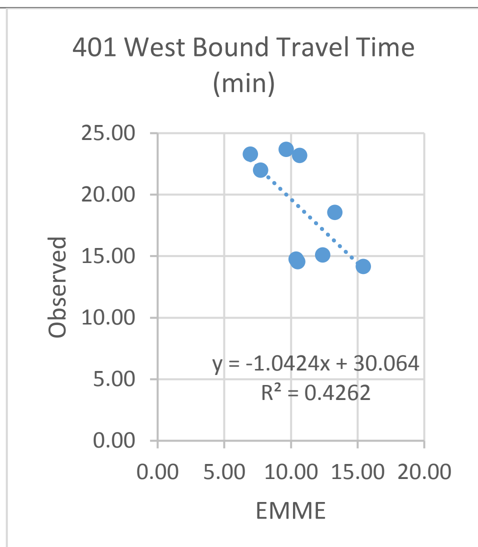
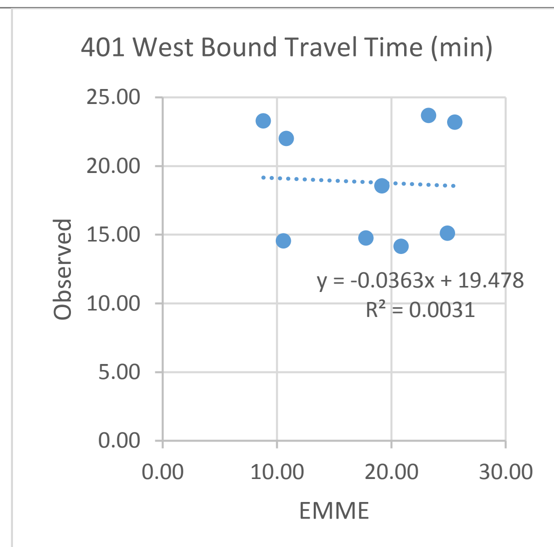
Other Highways Travel Time (min)
y = 0.109x + 13.061
R² = 0.1071
Observed
EMME

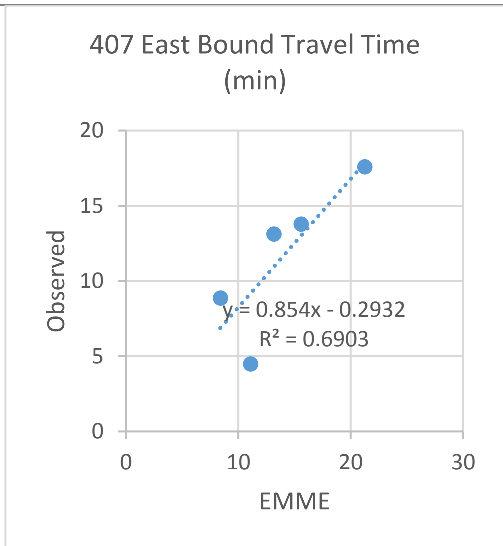
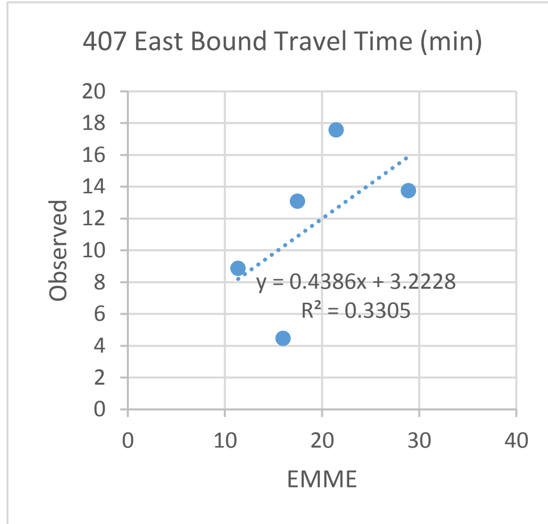
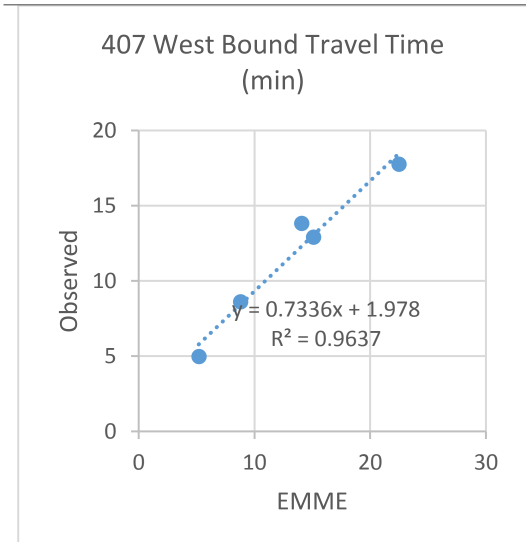
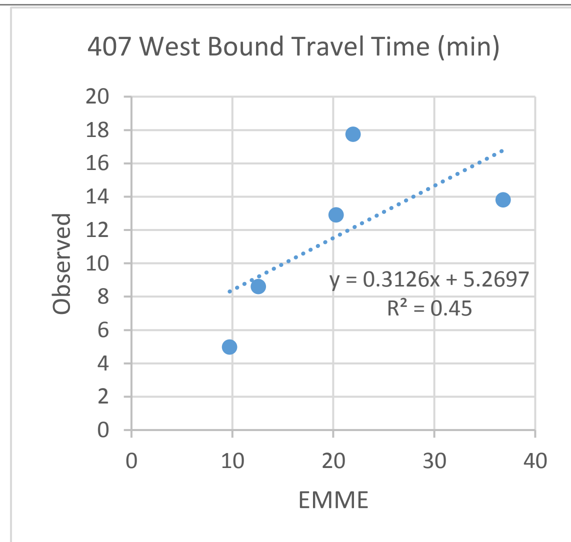
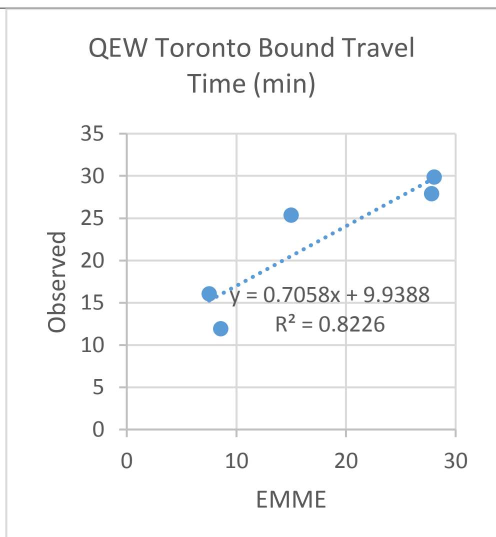
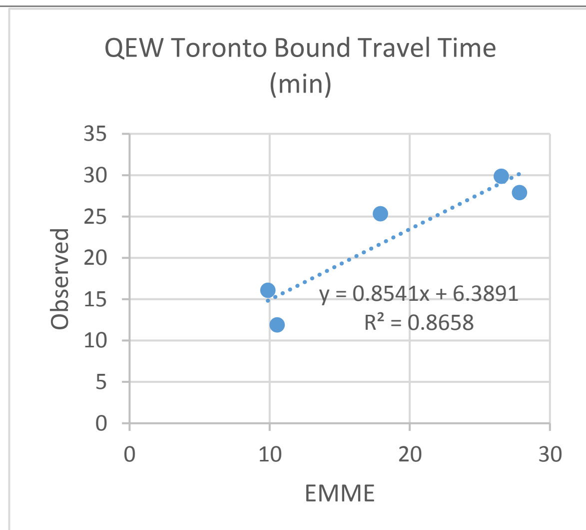
All Highways Travel Time (min)
y = 0.7832x + 6.4462
R² = 0.6658
Observed
EMME

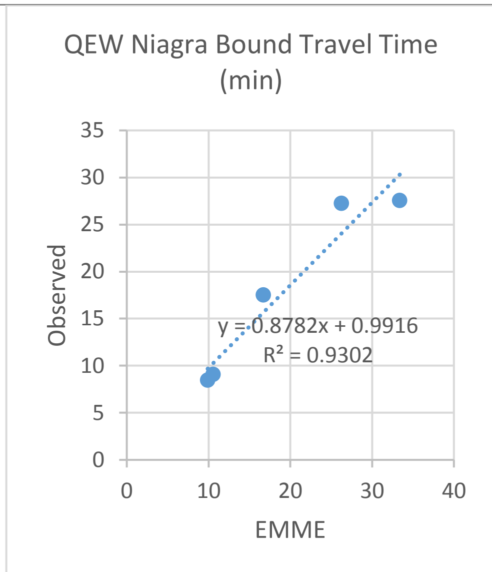
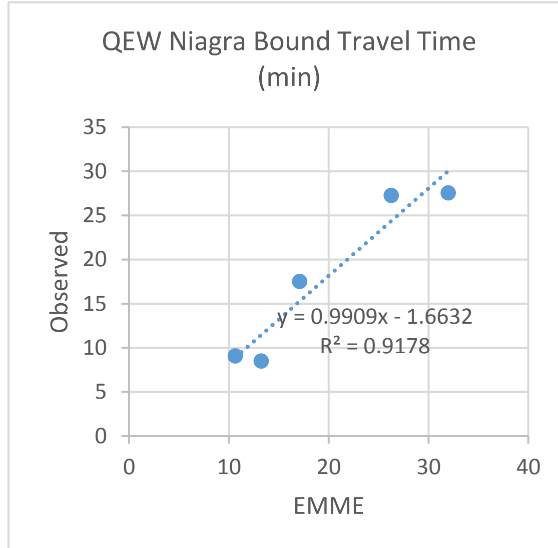
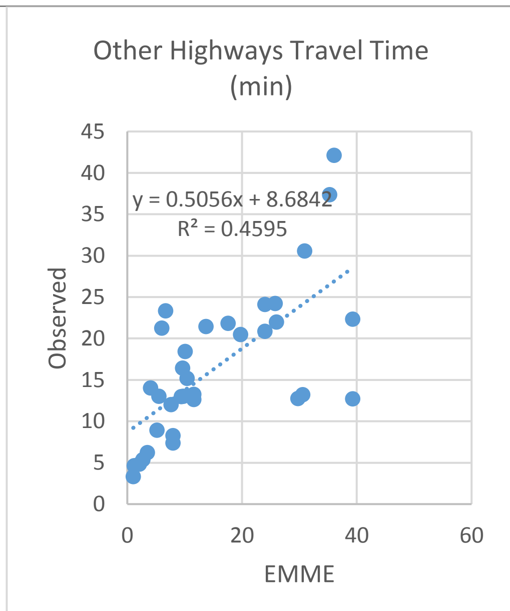
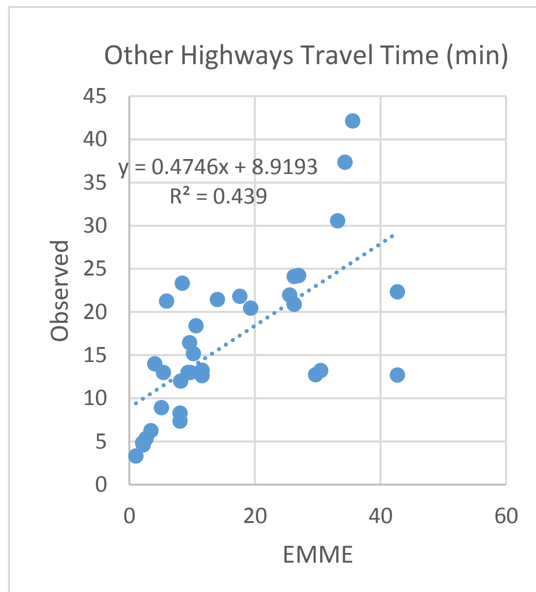
All Highways Travel Time (min)
y = 0.1006x + 12.892
R² = 0.1482
Observed
EMME

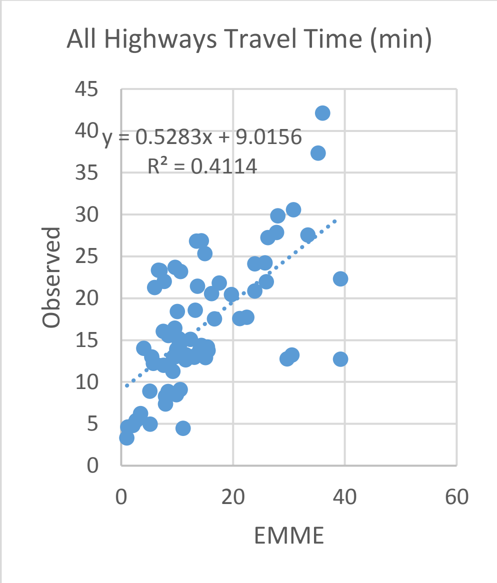
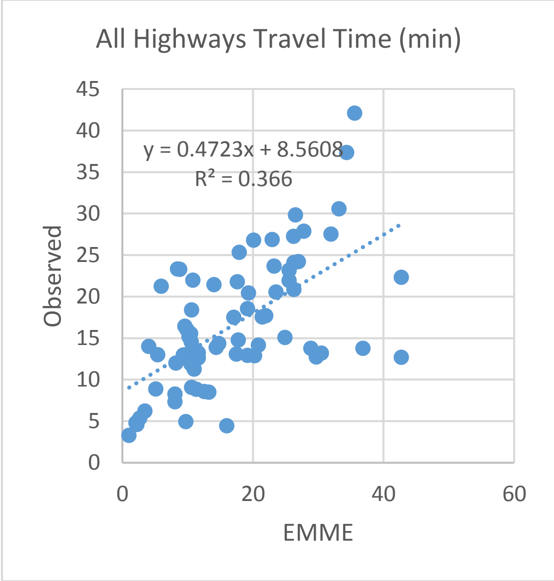
Appendix (B.2): Comparing the travel time before and after the adjustment (PM)

Table B.2- Comparing the travel time before and after the adjustment (PM)

<table>
<tr><th>5 pm</th><th>Before Adjustment</th><th>After Adjustment</th></tr>
<tr><td rowspan="2">401</td><td>
</td><td>
</td></tr>
<tr><td>
</td><td>
</td></tr>
</table>

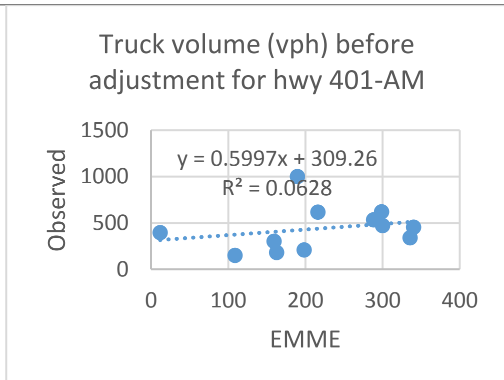
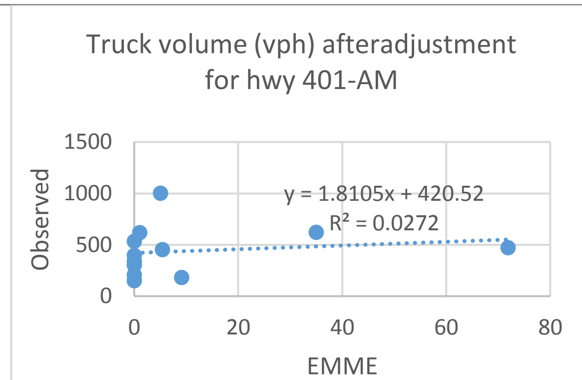
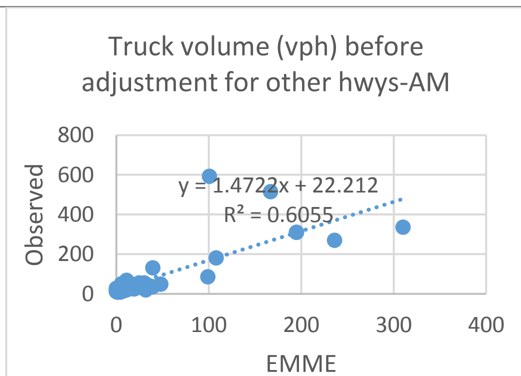
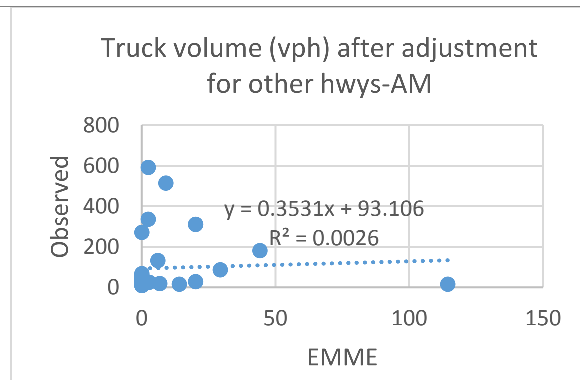
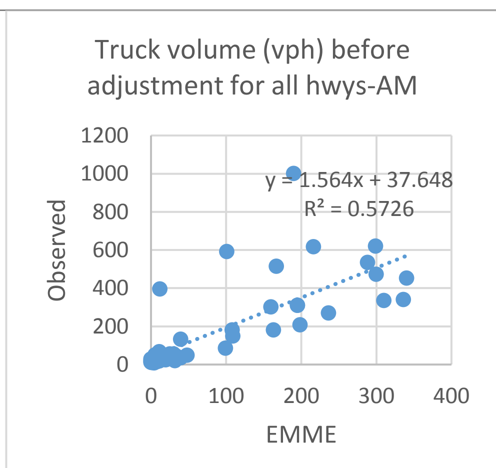
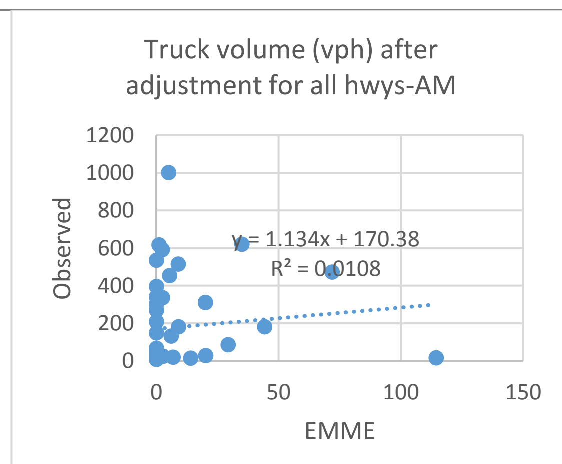
407	407 East Bound Travel Time (min)
Observed
EMME
y = 0.854x - 0.2932
R^2 = 0.6903	407 East Bound Travel Time (min)
Observed
EMME
y = 0.4386x + 3.2228
R^2 = 0.3305
	407 West Bound Travel Time (min)
Observed
EMME
y = 0.7336x + 1.978
R^2 = 0.9637	407 West Bound Travel Time (min)
Observed
EMME
y = 0.3126x + 5.2697
R^2 = 0.45
QEW	QEW Toronto Bound Travel Time (min)
Observed
EMME
y = 0.7058x + 9.9388
R^2 = 0.8226	QEW Toronto Bound Travel Time (min)
Observed
EMME
y = 0.8541x + 6.3891
R^2 = 0.8658

	QEW Niagra Bound Travel Time (min) y = 0.8782x + 0.9916 R² = 0.9302 Observed EMME	QEW Niagra Bound Travel Time (min) y = 0.9909x - 1.6632 R² = 0.9178 Observed EMME
Other	Other Highways Travel Time (min) y = 0.5056x + 8.6842 R² = 0.4595 Observed EMME	Other Highways Travel Time (min) y = 0.4746x + 8.9193 R² = 0.439 Observed EMME

All	All Highways Travel Time (min)
y = 0.5283x + 9.0156
R² = 0.4114
Observed
EMME
0
5
10
15
20
25
30
35
40
45
0
20
40
60	All Highways Travel Time (min)
y = 0.4723x + 8.5608
R² = 0.366
Observed
EMME
0
5
10
15
20
25
30
35
40
45
0
20
40
60

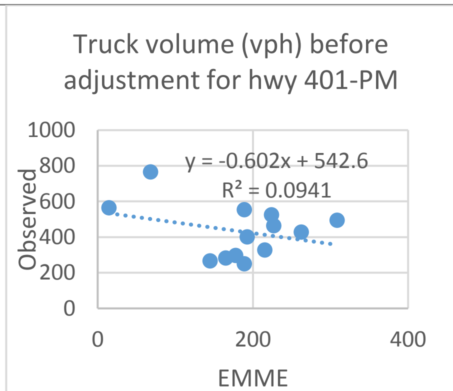
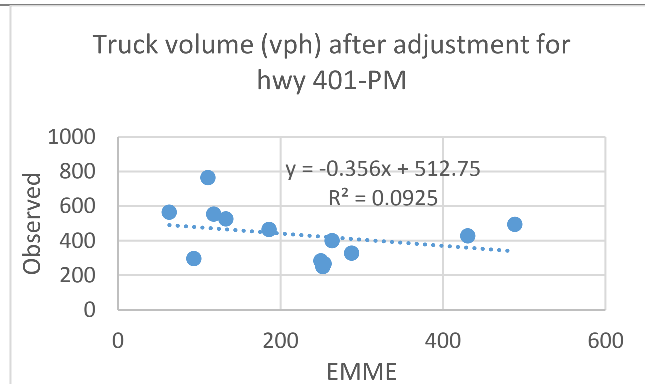
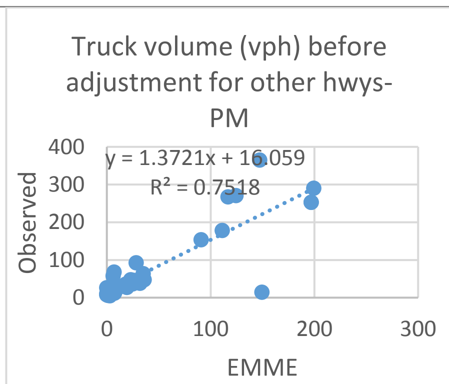
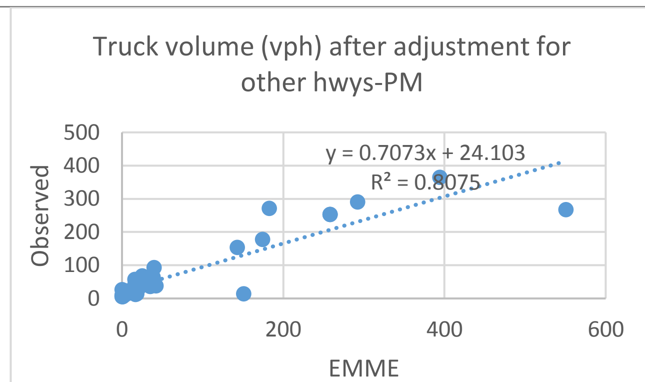
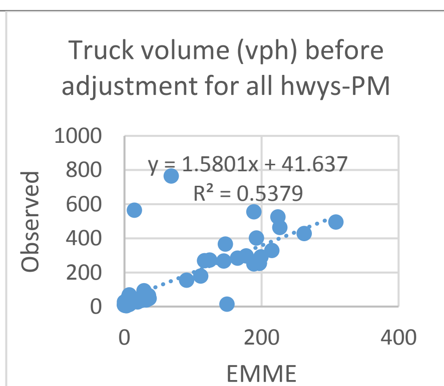
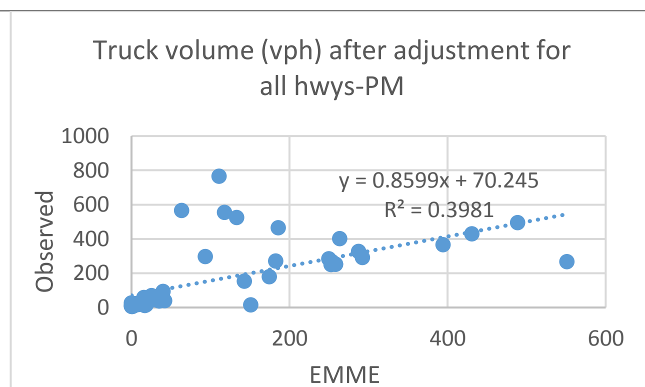
Appendix (B.3): Comparing the truck volume before and after the adjustment (AM)

Table B.3- Comparing the truck volume before and after the adjustment (AM)

8 am	Before Adjustment	After Adjustment
401		
Other		
All		

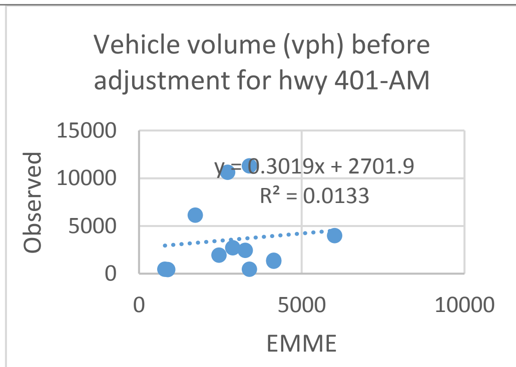
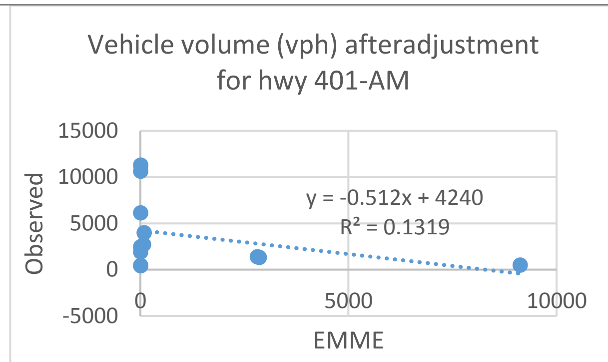
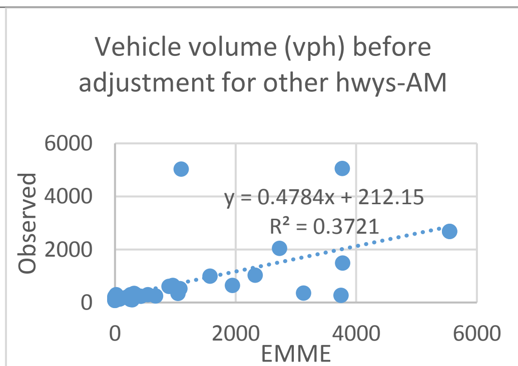
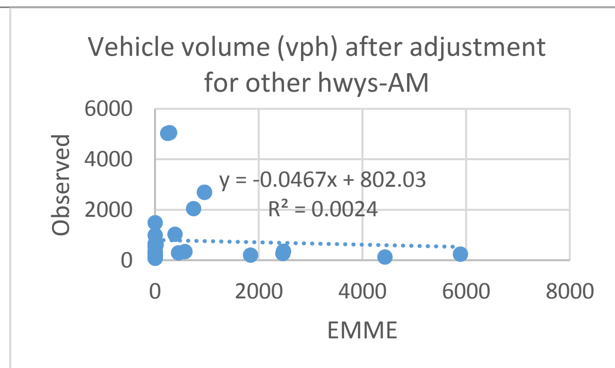
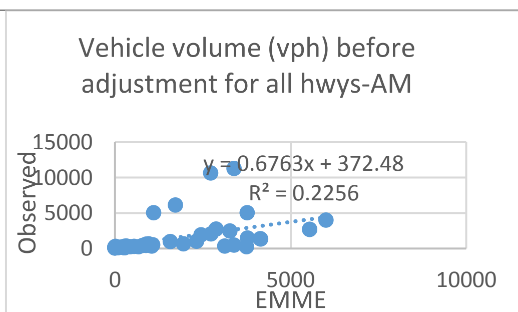
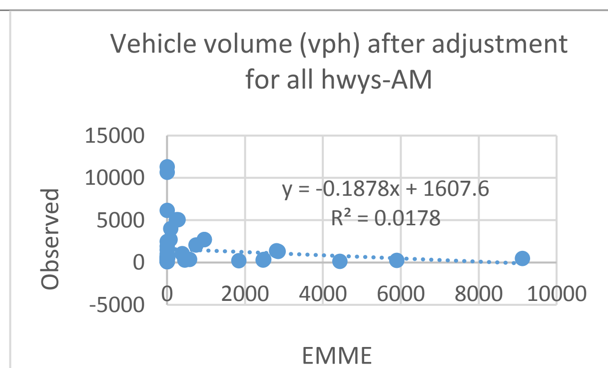
Appendix (B.4): Comparing the truck volume before and after the adjustment (PM)

Table B.4- Comparing the truck volume before and after the adjustment (PM)

<table>
<tr><th>5 pm</th><th>Before Adjustment</th><th>After Adjustment</th></tr>
<tr><td>401</td><td>
</td><td>
</td></tr>
<tr><td>Other</td><td>
</td><td>
</td></tr>
<tr><td>All</td><td>
</td><td>
</td></tr>
</table>

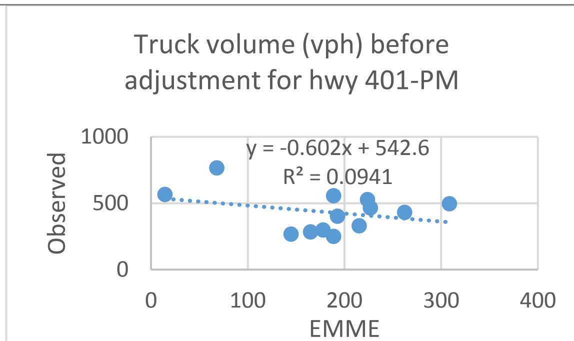
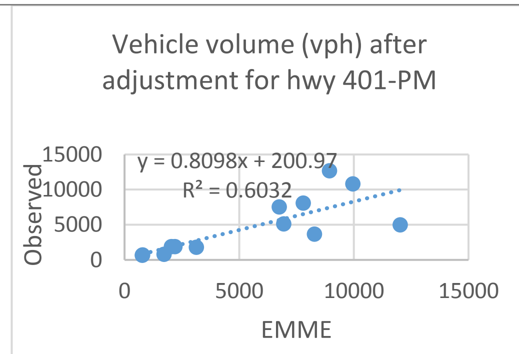
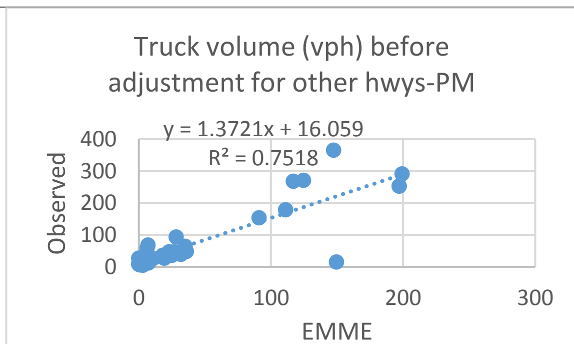
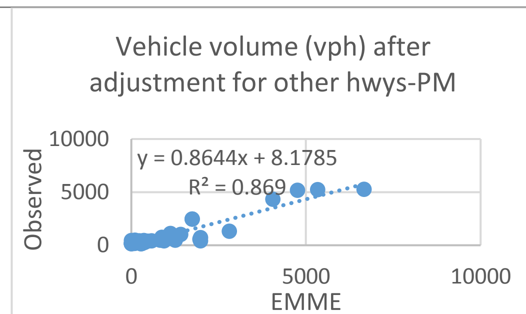
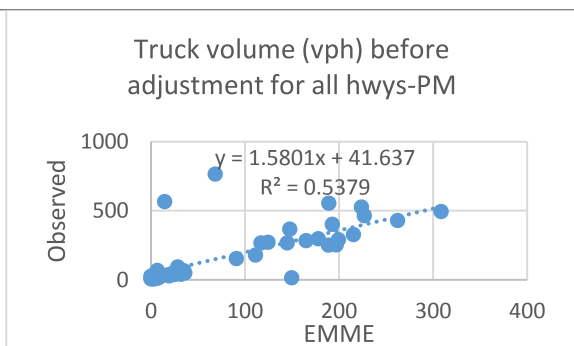
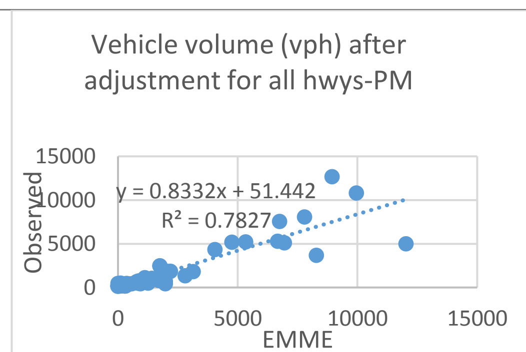
Appendix (B.5): Comparing the passenger car volume before and after the adjustment (AM)

Table B.5- Comparing the passenger car volume before and after the adjustment (AM)

<table>
<tr><th>8am</th><th>Before Adjustment</th><th>After Adjustment</th></tr>
<tr><td>401</td><td>
</td><td>
</td></tr>
<tr><td>Other</td><td>
</td><td>
</td></tr>
<tr><td>All</td><td>
</td><td>
</td></tr>
</table>

Appendix (B.6): Comparing the passenger car volume before and after the adjustment (PM)

Table B.6- Comparing the passenger car volume before and after the adjustment (PM)

<table>
<tr><th>5 pm</th><th>Before adjustment</th><th>After adjustment</th></tr>
<tr><td>401</td><td>
</td><td>
</td></tr>
<tr><td>Other</td><td>
</td><td>
</td></tr>
<tr><td>All</td><td>
</td><td>
</td></tr>
</table>

Appendix (B.7): Travel time before the adjustment (AM)

Table B.7- Travel time before the adjustment (AM)

Highway	Highway section	EMME	Observed
400	400 - North - Toronto Bound	32.66	37.36
	400 - North - Niagara Bound	37.7	42.12
	400 - South - Toronto Bound	9.34	12.99
	400 - South - Niagara Bound	25.97	24.23
403	403 - Hamilton -EB	24.2	24.12
	403 - Hamilton -WB	25.01	21.98
	403 - GPL - EB	24.2	24.12
	403 - GPL -WB	11.55	13.26
	403 - HOV - EB	24.2	20.89
	403 - HOV - WB	11.55	12.64
404	404 - GPL - North Bound	7.51	8.28
	404 - HOV - North Bound	7.51	7.37
405	405- East Bound	3.47	6.24
	405 - West Bound	5.13	8.92
406	406 - North Bound	5.59	13.01
	406 - South Bound	4.04	14.02
409	409 - East Bound	1.19	4.64
	409 - West Bound	1.03	3.31
410	410 - North Bound	7.34	12.02
	410 - South Bound	5.94	21.27
420	420 - East Bound	2.1	4.83
	420 - West Bound	2.67	5.38
427	427 - North Bound	9.72	13.02
	427 - South Bound	9.66	16.44
DVP	DVP - North Bound	9.16	15.18
	DVP - South Bound	13.52	21.45
Gardiner	Gardiner - East Bound	8.22	23.34
	Gardiner - West Bound	8.54	18.41
9	Hwy 9	30.86	30.68
10	Hwy 10	17.14	22.33
407	407 - Halton - North Bound	21.45	17.58
	407 - Halton - South Bound	21.75	17.74

	407 - Peel - East Bound	13.39	13.11
	407 - Peel - West Bound	14.71	12.9
	407 - York West - East Bound	5.17	4.48
	407 - York West - West Bound	5.17	4.97
	407 - York East - East Bound	11.05	8.87
	407- York East - west Bound	5.17	8.61
	407 - Durham - East Bound	14.82	13.78
	407 - Durham - west Bound	14.12	13.81
QEW	QEW Niagara - Toronto Bound	27.82	27.88
	QEW Niagara - Niagara Bound	26.22	27.27
	QEW Grimsby - Toronto Bound	29.75	29.86
	QEW Grimsby - Niagara Bound	30.77	27.56
	QEW Halton - Toronto Bound	15.32	25.35
	QEW Halton - Niagara Bound	15.67	17.54
	QEW East - Toronto Bound	8.41	16.07
	QEW East - Niagara Bound	9.04	8.5
	QEW HOV - Toronto Bound	8.79	11.91
	QEW HOV - Niagara Bound	9.87	9.09
401	401 Peel - East Bound	14.64	26.82
	401 Peel - West Bound	12.37	18.58
	401 CW - East Bound	8.49	15.56
	401 CW - West Bound	7.83	22.02
	401CE - East Bound	9.38	13.9
	401CE- West Bound	12.15	23.2
	401 West EXP - East Bound	17.28	20.57
	401 West EXP - West Bound	14.57	14.18
	401 Peel EXP- East Bound	15.84	26.89
	401 Peel EXP - West Bound	10.02	14.78
	401 CW EXP - East Bound	9.23	11.28
	401 CW EXP - West Bound	6.96	23.3
	401 CE EXP - East Bound	12.71	12.96
	401 CE EXP - West Bound	10.92	23.69
	401 Durham CE West EXP - East Bound	5.38	12.23
	401 Durham CE West EXP - West Bound	14.08	15.11
	401 Durham CE East EXP - East Bound	14.37	14.38
	401 Durham CE East EXP - West Bound	10.5	14.57

Appendix (B.8): Travel time before the adjustment (PM)

Table B.8- Travel time before the adjustment (PM)

Highway	Highway section	EMME	Observed
400	400 - North - Toronto Bound	32.66	37.36
	400 - North - Niagara Bound	37.7	42.12
	400 - South - Toronto Bound	9.34	12.99
	400 - South - Niagara Bound	25.97	24.23
403	403 - Hamilton -EB	24.2	24.12
	403 - Hamilton -WB	25.01	21.98
	403 - GPL - EB	24.2	24.12
	403 - GPL -WB	11.55	13.26
	403 - HOV - EB	24.2	20.89
	403 - HOV - WB	11.55	12.64
404	404 - GPL - North Bound	7.51	8.28
	404 - HOV - North Bound	7.51	7.37
405	405- East Bound	3.47	6.24
	405 - West Bound	5.13	8.92
406	406 - North Bound	5.59	13.01
	406 - South Bound	4.04	14.02
409	409 - East Bound	1.19	4.64
	409 - West Bound	1.03	3.31
410	410 - North Bound	7.34	12.02
	410 - South Bound	5.94	21.27
420	420 - East Bound	2.1	4.83
	420 - West Bound	2.67	5.38
427	427 - North Bound	9.72	13.02
	427 - South Bound	9.66	16.44
DVP	DVP - North Bound	9.16	15.18
	DVP - South Bound	13.52	21.45
Gardiner	Gardiner - East Bound	8.22	23.34
	Gardiner - West Bound	8.54	18.41
9	Hwy 9	30.86	30.68
10	Hwy 10	17.14	22.33
407	407 - Halton - North Bound	21.45	17.58
	407 - Halton - South Bound	21.75	17.74
	407 - Peel - East Bound	13.39	13.11

	407 - Peel - West Bound	14.71	12.9
	407 - York West - East Bound	5.17	4.48
	407 - York West - West Bound	5.17	4.97
	407 - York East - East Bound	11.05	8.87
	407- York East - west Bound	5.17	8.61
	407 - Durham - East Bound	14.82	13.78
	407 - Durham - west Bound	14.12	13.81
QEW	QEW Niagara - Toronto Bound	27.82	27.88
	QEW Niagara - Niagara Bound	26.22	27.27
	QEW Grimsby - Toronto Bound	29.75	29.86
	QEW Grimsby - Niagara Bound	30.77	27.56
	QEW Halton - Toronto Bound	15.32	25.35
	QEW Halton - Niagara Bound	15.67	17.54
	QEW East - Toronto Bound	8.41	16.07
	QEW East - Niagara Bound	9.04	8.5
	QEW HOV - Toronto Bound	8.79	11.91
	QEW HOV - Niagara Bound	9.87	9.09
401	401 Peel - East Bound	14.64	26.82
	401 Peel - West Bound	12.37	18.58
	401 CW - East Bound	8.49	15.56
	401 CW - West Bound	7.83	22.02
	401CE - East Bound	9.38	13.9
	401CE- West Bound	12.15	23.2
	401 West EXP - East Bound	17.28	20.57
	401 West EXP - West Bound	14.57	14.18
	401 Peel EXP- East Bound	15.84	26.89
	401 Peel EXP - West Bound	10.02	14.78
	401 CW EXP - East Bound	9.23	11.28
	401 CW EXP - West Bound	6.96	23.3
	401 CE EXP - East Bound	12.71	12.96
	401 CE EXP - West Bound	10.92	23.69
	401 Durham CE West EXP - East Bound	5.38	12.23
	401 Durham CE West EXP - West Bound	14.08	15.11
	401 Durham CE East EXP - East Bound	14.37	14.38
	401 Durham CE East EXP - West Bound	10.5	14.57

Appendix (B.9): Truck and passenger car volume before the adjustment (AM)

Table B.9-Truck and passenger car volume before the adjustment (AM)

Highway	ID	Truck volume-Emme	Truck volume-Observed	Vehicle volume- Emme	Vehicle volume-Observed
11	ON0126	30.00	54.80	1946.58	646.00
	ON0272	19.00	25.00	431.00	235.60
	ON0271	20.00	25.80	347.00	294.20
	ON0132	1.00	9.20	0.00	124.60
	ON0158	32.00	19.60	0.00	77.00
	ON0133	2.00	18.00	0.00	88.00
17	ON0134	6.00	26.80	25.00	116.00
QEW	ON0035	309.98	336.00	2730.06	2047.60
	ON0019	194.91	309.80	5545.99	2690.00
3	ON0266	1.13	15.60	260.82	130.60
	ON0019	194.91	309.80	5545.99	2690.00
6	ON0136	39.30	131.60	2325.23	1032.80
	ON0127	5.98	27.40	894.67	614.80
7	ON0124	6.57	14.60	278.00	141.20
	ON0316	5.43	50.80	192.83	202.80
	ON0261	0.00	28.40	19.85	294.60
	ON0125	7.99	15.00	258.00	115.40
	ON0317	11.12	67.80	258.98	298.00
	ON0270	15.83	49.80	1578.22	992.60
	ON0149	0.00	12.20	0.00	230.60
	ON0137	39.37	35.40	1078.13	527.00
	ON0138	24.78	54.80	958.10	649.00
	ON0297	0.00	19.00	0.00	204.80
	ON0298	3.00	12.60	252.76	158.20
	ON0099	4.00	8.40	283.00	103.80
	ON0113	2.00	15.40	673.00	250.80
	ON0152	10.11	25.00	1042.80	343.20
	ON0146	11.00	19.20	48.00	221.60

400	ON0100	37.00	37.40	66.00	132.40
	ON0150	48.00	49.40	316.00	352.60
	ON0021	236.22	270.60	3775.54	1488.60
	ON0101	25.00	34.40	85.00	139.20
	ON0151	34.00	44.20	548.00	303.80
	ON0031	108.01	181.80	3127.60	356.20
	ON0030	98.93	86.00	3748.11	269.80
	ON0026	166.79	514.80	3767.33	5061.20
	ON0027	100.68	592.00	1099.27	5037.60
401	ON0036	163.00	181.80	3390.00	475.60
	ON0028	299.86	472.00	4143.02	1317.40
	ON0032	216.32	616.80	6008.49	3996.60
	ON0116	189.92	1001.20	3390.88	11297.80
	ON0140	288.47	535.00	1725.01	6142.60
	ON0034	335.79	340.80	3269.28	2459.80
	ON0020	198.43	208.20	885.00	415.40
	ON0029	340.23	453.40	4136.37	1393.80
	ON0033	298.94	620.40	2883.14	2716.00
	ON0139	11.80	395.80	2721.78	10637.00
	ON0016	159.55	302.20	2454.75	1924.60
	ON0018	109.01	149.40	794.00	452.80

Appendix (B.10): Truck and passenger car volume before the adjustment (PM)

Table B.10- Truck and passenger car volume before the adjustment (PM)

Highway	ID	Truck volume- Emme	Truck volume- Observed	Vehicle volume- Emme	Vehicle volume- Observed
11	ON0126	35.00	64.40	2150.00	1024.60
	ON0272	20.00	33.20	478.00	389.40
	ON0271	18.00	36.20	382.00	272.60
	ON0132	1.00	19.60	0.00	138.40
	ON0158	23.00	47.60	0.00	170.20
	ON0133	4.00	17.40	0.00	149.40
17	ON0134	6.00	23.20	27.00	357.60
QEW	ON0035	199.29	290.80	4834.46	4334.80
	ON0019	197.00	253.00	4401.95	2451.20
3	ON0266	2.02	9.80	336.89	151.80
	ON0019	197.00	253.00	4401.95	2451.20
6	ON0136	28.31	93.20	2993.07	1318.40
	ON0127	3.00	21.20	993.01	485.80
7	ON0124	7.21	12.20	307.00	177.00
	ON0316	6.15	57.80	214.11	422.40
	ON0261	0.00	27.00	8.82	478.80
	ON0125	4.94	14.20	284.00	223.40
	ON0317	6.83	68.60	284.83	229.40
	ON0270	10.75	26.60	1264.53	487.40
	ON0149	0.00	8.00	0.00	451.00
	ON0137	26.10	46.40	1130.55	1110.60
	ON0138	19.20	27.60	1034.91	734.60
	ON0297	0.00	10.60	0.00	159.00
	ON0296	149.60	14.60	4533.99	718.40
	ON0298	1.00	6.20	277.70	151.60
	ON0099	3.00	5.40	313.00	176.80
	ON0113	3.00	9.60	743.00	381.40

	ON0152	6.87	18.40	1014.23	411.20
	ON0146	8.00	16.20	53.00	373.00
400	ON0100	25.00	36.60	73.00	165.00
	ON0150	32.00	38.80	355.80	453.00
	ON0021	124.58	271.40	5908.81	5161.40
	ON0101	27.00	45.80	94.00	171.20
	ON0151	36.00	48.40	604.00	422.20
	ON0031	90.87	154.00	3455.06	424.20
	ON0030	111.21	178.60	3755.79	576.60
	ON0026	147.43	365.60	2763.95	5260.80
	ON0027	116.81	267.80	3211.26	5222.60
401	ON0036	188.81	250.00	3471.97	788.00
	ON0028	308.50	494.20	4372.99	1851.80
	ON0032	223.89	525.60	5045.02	3661.00
	ON0116	188.91	554.40	3133.43	8050.40
	ON0140	177.76	296.80	5222.69	12673.40
	ON0034	192.64	400.60	6076.72	4981.60
	ON0020	144.79	266.80	976.00	653.40
	ON0029	262.24	428.60	4319.95	1855.40
	ON0033	226.89	464.20	4227.60	5101.20
	ON0115	68.12	765.60	877.81	10782.20
	ON0139	14.57	565.00	808.03	7529.00
	ON0016	215.27	327.60	2905.83	1797.20
	ON0018	165.06	283.20	878.00	662.00

Appendix (B.11): Travel time after the adjustment (AM)

Table B.11- Travel time after the adjustment (AM)

Highway	Highway section	EMME	Observed
400	400 - North - Toronto Bound	22.03	37.36
	400 - North - Niagara Bound	39.39	42.12
	400 - South - Toronto Bound	23.10	12.99
	400 - South - Niagara Bound	33.75	24.23
403	403 - Hamilton -EB	86.05	24.12
	403 - Hamilton -WB	62.15	21.98
	403 - GPL - EB	86.05	24.12
	403 - GPL -WB	49.27	13.26
	403 - HOV - EB	86.05	20.89
	403 - HOV - WB	49.27	12.64
404	404 - GPL - North Bound	20.27	8.28
	404 - HOV - North Bound	20.27	7.37
405	405- East Bound	8.36	6.24
	405 - West Bound	2.62	8.92
406	406 - North Bound	21.70	13.01
	406 - South Bound	8.38	14.02
409	409 - East Bound	1.15	4.64
	409 - West Bound	3.87	3.31
410	410 - North Bound	49.58	12.02
	410 - South Bound	49.36	21.27
420	420 - East Bound	16.27	4.83
	420 - West Bound	12.39	5.38
427	427 - North Bound	26.98	13.02
	427 - South Bound	113.66	16.44
DVP	DVP - North Bound	20.82	15.18
	DVP - South Bound	42.17	21.45
Gardiner	Gardiner - East Bound	15.55	23.34
	Gardiner - West Bound	33.25	18.41
9	Hwy 9	11.61	30.68

10	Hwy 10	12.54	22.33
407	407 - Halton - North Bound	55.88	17.58
	407 - Halton - South Bound	54.08	17.74
	407 - Peel - East Bound	50.29	13.11
	407 - Peel - West Bound	108.08	12.90
	407 - York West - East Bound	16.26	4.48
	407 - York West - West Bound	9.61	4.97
	407 - York East - East Bound	35.86	8.87
	407- York East - west Bound	9.61	8.61
	407 - Durham - East Bound	38.98	13.78
	407 - Durham - west Bound	24.07	13.81
QEW	QEW Niagara - Toronto Bound	87.45	27.88
	QEW Niagara - Niagara Bound	85.14	27.27
	QEW Grimsby - Toronto Bound	49.04	29.86
	QEW Grimsby - Niagara Bound	30.43	27.56
	QEW Halton - Toronto Bound	48.04	25.35
	QEW Halton - Niagara Bound	33.82	17.54
	QEW East - Toronto Bound	26.12	16.07
	QEW East - Niagara Bound	26.29	8.50
	QEW HOV - Toronto Bound	24.16	11.91
	QEW HOV - Niagara Bound	21.46	9.09
401	401 Peel - East Bound	139.80	26.82
	401 Peel - West Bound	120.19	18.58
	401 CW - East Bound	30.18	15.56
	401 CW - West Bound	57.07	22.02
	401CE - East Bound	82.25	13.90
	401CE- West Bound	77.88	23.20
	401 West EXP - East Bound	47.87	20.57
	401 West EXP - West Bound	30.94	14.18
	401 Peel EXP- East Bound	42.33	26.89
	401 Peel EXP - West Bound	42.79	14.78
	401 CW EXP - East Bound	14.30	11.28
	401 CW EXP - West Bound	7.26	23.30

	401 CE EXP - East Bound	24.90	12.96
	401 CE EXP - West Bound	28.25	23.69
	401 Durham CE West EXP - East Bound	7.37	12.23
	401 Durham CE West EXP - West Bound	24.90	15.11
	401 Durham CE East EXP - East Bound	10.44	14.38
	401 Durham CE East EXP - West Bound	12.87	14.57

Appendix (B.12): Travel time after the adjustment (PM)

Table B.12- Travel time after the adjustment (PM)

Highway	Highway section	EMME	Observed
400	400 - North - Toronto Bound	34.37	37.36
	400 - North - Niagara Bound	35.58	42.12
	400 - South - Toronto Bound	9.35	12.99
	400 - South - Niagara Bound	19.34	20.47
403	403 - Hamilton -EB	26.97	24.23
	403 - Hamilton -WB	25.53	21.98
	403 - GPL - EB	26.25	24.12
	403 - GPL -WB	11.61	13.26
	403 - HOV - EB	26.25	20.89
	403 - HOV - WB	11.61	12.64
404	404 - GPL - North Bound	8.06	8.28
	404 - GPL - South Bound	42.72	22.34
	404 - HOV - North Bound	8.06	7.37
	404 - HOV - South Bound	42.72	12.71
405	405- East Bound	3.47	6.24
	405 - West Bound	5.13	8.92
406	406 - North Bound	5.43	13.01
	406 - South Bound	4.04	14.02
409	409 - East Bound	2.22	4.64
	409 - West Bound	1.04	3.31
410	410 - North Bound	8.20	12.02
	410 - South Bound	5.95	21.27
420	420 - East Bound	2.10	4.83
	420 - West Bound	2.67	5.38
427	427 - North Bound	9.72	13.02
	427 - South Bound	9.59	16.44
DVP	DVP - North Bound	10.21	15.18
	DVP - South Bound	14.04	21.45
Gardiner	Gardiner - East Bound	8.44	23.34

	Gardiner - West Bound	10.63	18.41
35	Hwy 35 - North Bound	30.49	13.24
	Hwy 35 - South Bound	29.69	12.76
9	Hwy 9	33.19	30.58
10	Hwy 10	17.62	21.82
407	407 - Halton - North Bound	21.44	17.58
	407 - Halton - South Bound	21.96	17.74
	407 - Peel - East Bound	17.45	13.11
	407 - Peel - West Bound	20.26	12.90
	407 - York West - East Bound	15.99	4.48
	407 - York West - West Bound	9.73	4.97
	407 - York East - East Bound	11.35	8.87
	407- York East - west Bound	12.57	8.61
	407 - Durham - East Bound	28.87	13.78
	407 - Durham - west Bound	36.83	13.81
QEW	QEW Niagara - Toronto Bound	27.82	27.88
	QEW Niagara - Niagara Bound	26.25	27.27
	QEW Grimsby - Toronto Bound	26.53	29.86
	QEW Grimsby - Niagara Bound	31.98	27.56
	QEW Halton - Toronto Bound	17.90	25.35
	QEW Halton - Niagara Bound	17.09	17.54
	QEW East - Toronto Bound	9.86	16.07
	QEW East - Niagara Bound	13.24	8.50
	QEW HOV - Toronto Bound	10.52	11.91
	QEW HOV - Niagara Bound	10.62	9.09
401	401 Peel - East Bound	20.12	26.82
	401 Peel - West Bound	19.17	18.58
	401 CW - East Bound	10.46	15.56
	401 CW - West Bound	10.81	22.02
	401CE - East Bound	14.37	13.90
	401CE- West Bound	25.56	23.20
	401 West EXP - East Bound	23.54	20.57
	401 West EXP - West Bound	20.85	14.18

	401 Peel EXP- East Bound	22.96	26.89
	401 Peel EXP - West Bound	17.76	14.78
	401 CW EXP - East Bound	11.00	11.28
	401 CW EXP - West Bound	8.80	23.30
	401 CE EXP - East Bound	19.17	12.96
	401 CE EXP - West Bound	23.24	23.69
	401 Durham CE West EXP - East Bound	10.38	12.23
	401 Durham CE West EXP - West Bound	24.91	15.11
	401 Durham CE East EXP - East Bound	14.77	14.38
	401 Durham CE East EXP - West Bound	10.56	14.57

Appendix (B.13): Truck and passenger car volume after the adjustment (AM)

Table B.13- Truck and passenger car volume after the adjustment (AM)

Highway	ID	Truck volume-Emme	Truck volume-Observed	Vehicle volume-Emme	Vehicle volume-Observed
11	ON0126	0.00	54.80	0.00	646.00
	ON0272	0.00	25.00	0.00	235.60
	ON0271	0.00	25.80	0.00	294.20
	ON0132	0.00	9.20	0.00	124.60
	ON0158	0.00	19.60	0.00	77.00
	ON0133	0.00	18.00	0.00	88.00
17	ON0134	0.00	26.80	0.00	116.00
QEW	ON0035	2.47	336.00	739.28	2047.60
	ON0019	20.09	309.80	953.54	2690.00
3	ON0266	114.44	15.60	4435.20	130.60
	ON0019	20.09	309.80	953.54	2690.00
6	ON0136	6.01	131.60	385.93	1032.80
	ON0127	1.28	27.40	19.96	614.80
7	ON0124	0.00	14.60	0.00	141.20
	ON0316	0.00	50.80	0.00	202.80
	ON0261	20.12	28.40	452.98	294.60
	ON0125	0.00	15.00	0.00	115.40
	ON0317	0.00	67.80	0.00	298.00
	ON0270	0.00	49.80	0.00	992.60
	ON0149	0.00	12.20	0.00	230.60
	ON0137	0.00	35.40	0.00	527.00
	ON0138	0.00	54.80	0.00	649.00
	ON0297	6.77	19.00	1840.13	204.80
	ON0298	0.00	12.60	0.00	158.20
	ON0099	0.00	8.40	0.00	103.80
	ON0113	14.00	15.40	5890.77	250.80
	ON0152	2.79	25.00	575.35	343.20

	ON0146	0.00	19.20	0.00	221.60
400	ON0100	0.00	37.40	0.00	132.40
	ON0150	0.00	49.40	0.00	352.60
	ON0021	0.00	270.60	0.00	1488.60
	ON0101	0.00	34.40	0.00	139.20
	ON0151	0.00	44.20	0.00	303.80
	ON0031	44.22	181.80	2478.28	356.20
	ON0030	29.35	86.00	2465.75	269.80
	ON0026	8.96	514.80	281.37	5061.20
	ON0027	2.38	592.00	240.05	5037.60
401	ON0036	9.09	181.80	9119.41	475.60
	ON0028	71.89	472.00	2850.74	1317.40
	ON0032	1.04	616.80	89.35	3996.60
	ON0116	5.02	1001.20	0.00	11297.80
	ON0140	0.00	535.00	0.00	6142.60
	ON0034	0.00	340.80	0.00	2459.80
	ON0020	0.00	208.20	0.00	415.40
	ON0029	5.43	453.40	2807.81	1393.80
	ON0033	35.01	620.40	74.02	2716.00
	ON0139	0.00	395.80	0.00	10637.00
	ON0016	0.00	302.20	0.00	1924.60
	ON0018	0.00	149.40	0.00	452.80

Appendix (B.14): Truck and passenger car volume after the adjustment (PM)

Table B.14- Truck and passenger car volume after the adjustment (PM)

Highway	ID	Truck volume- Emme	Truck volume- Observed	Vehicle volume- Emme	Vehicle volume- Observed
11	ON0126	38.78	64.40	1416.54	1024.60
	ON0272	21.34	33.20	459.22	389.40
	ON0271	20.34	36.20	375.64	272.60
	ON0132	1.06	19.60	0.00	138.40
	ON0158	29.51	47.60	0.00	170.20
	ON0133	4.07	17.40	0.00	149.40
17	ON0134	6.18	23.20	28.85	357.60
QEW	ON0035	292.13	290.80	4050.75	4334.80
	ON0019	258.07	253.00	1743.94	2451.20
3	ON0266	1.00	9.80	274.70	151.80
	ON0019	258.07	253.00	1743.94	2451.20
6	ON0136	39.83	93.20	2806.05	1318.40
	ON0127	3.17	21.20	830.82	485.80
7	ON0124	16.66	12.20	303.69	177.00
	ON0316	15.84	57.80	228.89	422.40
	ON0261	0.00	27.00	101.51	478.80
	ON0125	18.53	14.20	281.80	223.40
	ON0317	25.31	68.60	292.45	229.40
	ON0270	14.92	26.60	1258.09	487.40
	ON0149	0.00	8.00	0.00	451.00
	ON0137	16.55	46.40	1116.06	1110.60
	ON0138	15.32	27.60	871.87	734.60
	ON0297	0.00	10.60	0.00	159.00
	ON0296	150.81	14.60	1982.27	718.40
	ON0298	0.20	6.20	273.17	151.60

	ON0099	1.06	5.40	301.76	176.80
	ON0113	2.75	9.60	337.36	381.40
	ON0152	8.18	18.40	940.40	411.20
	ON0146	8.30	16.20	56.65	373.00
400	ON0100	35.06	36.60	73.90	165.00
	ON0150	42.05	38.80	361.21	453.00
	ON0021	182.55	271.40	4757.61	5161.40
	ON0101	30.63	45.80	93.75	171.20
	ON0151	39.81	48.40	578.23	422.20
	ON0031	142.97	154.00	1981.29	424.20
	ON0030	174.21	178.60	1959.46	576.60
	ON0026	394.15	365.60	6663.53	5260.80
	ON0027	550.87	267.80	5330.69	5222.60
401	ON0036	252.37	250.00	1720.28	788.00
	ON0028	488.48	494.20	2193.89	1851.80
	ON0032	133.00	525.60	8284.27	3661.00
	ON0116	117.84	554.40	7789.30	8050.40
	ON0140	93.34	296.80	8938.56	12673.40
	ON0034	263.40	400.60	12026.15	4981.60
	ON0020	253.83	266.80	774.87	653.40
	ON0029	430.77	428.60	2038.96	1855.40
	ON0033	185.85	464.20	6943.81	5101.20
	ON0115	110.77	765.60	9955.22	10782.20
	ON0139	63.24	565.00	6749.46	7529.00
	ON0016	287.47	327.60	3134.51	1797.20
	ON0018	249.67	283.20	794.90	662.00

Appendix (C)

Appendix C: Ontario's maps

Figure C.1- Average Annual Daily Traffic (AADT) (2008) * represents IDs 1-10

Figure C.2- Value of Good (VOG) (2008) * represents IDs 1-10