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A New Design and Environment Evaluation Approach for Managed Lanes on a Freeway Facility

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A New Design and Environment Evaluation Approach for Managed Lanes on a Freeway Facility

by

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Abstract

In this thesis, a new design and environmental evaluation of the managed lane is presented. HOV/HOT lane is an efficient transportation strategy aims to mitigate the congestion by tolling freeway. In the first part of this study, a dynamic toll pricing approach was taken to minimize the total passenger travel time of the tolled freeway. The model was tested using a PARAMICS microsimulation model on a section of the Deerfoot Trail in Calgary, Alberta. The environmental impact of the proposed model is determined using PARAMICS Monitor. In the second part of this study, the long-term impacts of deploying transportation strategies on greenhouse gas (GHG) emission is evaluated. While previous studies relied only on simulation results, this study uses Leontief's input-output (I-O) model to capture the large-scale environmental impacts of transportation strategies. The I-O model was utilized to assess the impacts of improvements on the induced demand and evaluate the environmental impact of transportation strategy. The transportation strategies effects were estimated in terms of congestion reduction savings, to identify the industries that would be affected. The environmental impact in terms of changes in GHG emissions was conducted for all affected industries. A case study was also conducted on HOV/HOT lane deployment in Deerfoot Trail described in the first part. A sensitivity analysis was conducted for the level of GHG emission savings enhanced by transportation strategies for Calgary and Edmonton, which are two major Alberta cities that are similar in size, population and congestion level to compare the results. The results of the study show that the traditional approaches that focus on simply evaluating the short-term impacts of these strategies considerably overestimate the reduction of GHG emissions. Another major finding of this study is that deploying transportation strategies that would result in the same reduction in congestion levels is shown to result in significantly different long-term impacts on GHG emissions of the two

examined cities. This is mainly attributed to the difference in the structure of the economic and industrial sectors in the two cities.

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CHAPTER ONE: INTRODUCTION

1.1 Overview

Traffic congestion is regularly cited by citizens as one of the most challenging issues in growing urban areas. Congestion is mainly concentrated on critical urban freeways and arterials, and occurs mainly during peak traffic hours (recurrent congestion) or during incidents (non-recurrent congestion). Like any growing city in the world, traffic congestion is a common traffic problem in the City of Calgary (Calgary Herald, 2012).

In addition to the negative impacts of congestion on the economy of the city, traffic congestion can affect public health in two major ways:

- Direct impact: Traffic collision and safety issues

  Long queues on freeways resulting from traffic congestion can create shockwaves which might urge drivers to suddenly decelerate to avoid collision with the cars at the back of the queue. This can potentially increase the probability of traffic collisions and consequently endanger the drivers' safety.

- Indirect impact: Vehicle exhaust emission

  Unlike the direct impact of traffic congestion on the drivers' safety, this indirect impact is not restricted to the people who are driving on that specific congested freeway or street. The GHG emitted from vehicle exhaust along with other emitted toxic gases, such as carbon monoxide (CO), and particular matter (PM_{10} and $PM_{2.5}$) can affect the well-being of not only the car users, but also people who are living in the vicinity of the highly travelled corridors. It can even affect residents in other regions by causing long-term worldwide effects, such as acid rain and global warming (Barth and Boriboonsomsin, 2009).

The global warming is the consequence of excessive presence of the greenhouse gases in atmosphere. The Earth's Greenhouse effect is a natural occurrence which regulates the temperature of the earth. When sun heats the Earth, some of this heat is reflected back to the space. The rest of the heat is trapped by the greenhouse gases like water vapor and carbon dioxide (CO_2) which helps to regulating the temperature (EPA, 2009). Human based activities have affected the natural greenhouse gas effect by increasing 30% GHG concentration level to the atmosphere, very likely causing the Earth's average temperature to rise. If human continue to emit the GHG at or above the current level, it will increase the average Earth's temperature by 3 to 7˚F by 2100 (EPA, 2009). This huge increase in the temperature will increase precipitation, see levels, and the frequency of some extreme whether which literally affects the human health, agriculture, forests, water resources, energy and wildlife.

Transportation sector as a big contributor to GHG emissions is responsible for 24% of greenhouse gas (GHG) emissions in Canada (Environment Canada, 2014). Since traffic congestion is a major source of GHG emissions in transportation network, efficient transportation strategies should be considered to mitigate traffic congestion and consequently transportation GHG emission.

As congestion is a major source of fuel consumption and greenhouse emissions (GHGs), it also has major impacts on both the environment and the economy.

1. *Impact on economy*: Congestion prohibits the free flow of goods and people, and is a major source of delay. There are two measures to derive the economic cost of congestion:

➢ Annual delay time cost: More than 90% of total congestion cost represents the value of the time lost to auto travelers (Transport Canada, 2006 A).

- Annual wasted fuel volume cost: 6,070,000 liters of gasoline are wasted due to the congestion situation in Calgary each year. The cost of this amount of wasted fuel represents about 7% of total congestion cost (Transport Canada, 2006 A).

2. *Impact on environment:* The vehicles would have their maximum exhaust emissions when they are moving slowly or stopping at the queues in the congested motorways. So, the more is the total congestion time, the more is the total GHG emitted from vehicles' tailpipes. The cost of the environmental impact of congestion constitutes 3% of total congestion cost in the City of Calgary (Transport Canada, 2006 A).

There are three main criteria for calculating the congestion cost:

- Annual amount of travel delay (i.e., lost time) , measured in vehicle hours of travel;
- Annual wasted fuel volume;
- Annual GHG emission volume.

The first indicator is mainly a loss to the economy, but is also a social loss in terms of time not available for individuals to use for other purposes. The second indicator, wasted fuel, has both an economic cost and an environmental cost. The final indicator, carbon emissions into the atmosphere, has consequences for the economy now and for the environment in the years ahead. In 2006, total Canada congestion cost was $5,555 million Canadian dollars annually (Transport Canada, 2006 B), and Calgary total congestion cost was about 121 million Canadian dollars and constituted 3.7% of the national congestion cost per annum in that year. Moreover Calgary was the 5th most congested city in Canada after Vancouver, Toronto, Montreal, and Ottawa in 2014 (Tom Tom International BV, 2013)

With the increasing population of cities, existing urban road transportation systems are facing severe problems of capacity shortages, congestion, and pollution. Due to fiscal, land and environmental constraints, network expansion is often not a viable solution, especially in urban areas. Transportation Demand Management (TDM) is an instrumental strategy in achieving sustainable transportation solutions. TDM focuses on influencing travel behavior by applying strategies and policies to reduce automobile travel demand or redistribute this demand in space (i.e., to less congested roads) or in time (i.e., influencing travel to shift from peak hours to off-peak hours). The primary aim of TDM is to conserve energy, improve air quality, and control traffic congestion. Congestion pricing is shown to be one of the most efficient TDM strategies in reducing congestion.

Congestion pricing is based on the economic concept of supply and demand, i.e., when the price of a commodity increases, the demand decreases. Congestion pricing can be implemented as a fixed price or as a dynamic traffic scheme (i.e., during AM and PM rush hours or in response to traffic congestion). Pricing schemes can be implemented at a cordon level (e.g., London downtown), on a whole freeway facility (i.e., Highway 407 in Toronto), or on a specific lane. Congestion pricing can consequently ease congestion and decrease the greenhouse gas emissions from motor vehicles.

Recently, there has been an increased interest in implementation of dynamic shoulder lane use which allows shoulders to operate as a high occupancy vehicle/high occupancy toll (HOV/HOT) lane during heavy traffic and then switch back to a shoulder (i.e., closed) during other periods of the day. HOV/HOT lane is free to use for high occupancy vehicles (HOV) and transit while single occupancy vehicles (SOV) need to pay toll to travel in the lane. This type of managed lane (ML) facilities (also known as express lane) is increasingly being considered as a promising strategy to address transportation system problems, and has been implemented in the U.S. and in Europe. While the toll rate is determined at some facilities based on historical data, the toll rate is set dynamically on prevailing travelling conditions with the objective of guaranteeing a minimum level of service (Michalaka et al., 2011). HOV/HOT lanes encourage some travelers to use transit, carpools, or generate additional revenue from SOV who are ready to pay for a shorter travel-time and better travel-time reliability.

Since the transportation sector is responsible for 24% of greenhouse gas (GHG) emissions in Canada (Environment Canada, 2014), the reduction in congestion and delays resulting from congestion pricing is also expected to lead to reductions in energy consumption and GHG emissions at the city level. The vision of congestion pricing is to promote the development of a balanced and sustainable transportation system, providing the region with reasonable and affordable transportation choices (CAEP, 2010).

1.2 Problem Statement and Proposed Methodology

As discussed previously in section 1.1, managed lanes in the form of HOV/HOT lanes aim to mitigate congestion on the freeways during peak hours and/or during non-recurrent congestion (incidents, special events, construction, etc.). However, to the best of our knowledge, among the previous studies about HOV/HOT implementation, none have dealt with congestion reduction directly. In most of these studies, congestion was priced to either maximize the throughput or toll revenue, or both (refer to Chapter Two for more details). Thus, these strategies are not able to maximize congestion reduction. Since total network travel-time is directly linked to network congestion, minimizing total passenger travel-time on all lanes (i.e. HOV/HOT and general purpose (GP) lanes) was chosen as the main objective of this study to minimize the negative impacts of congestion, such as delayed time, wasted fuel, and excessive GHG emission due to the traffic congestion.

To assess the short-term impact of the proposed methodology on total congestion cost, QUADSTONE PARAMICS traffic micro simulator was chosen. PARAMICS is capable of providing complete details of savings in travel time, wasted fuel, and GHG emissions associated with each car, route, or section in the model.

Most of the previous studies have concentrated on evaluating the short-term direct environmental impact of transportation improvements, including savings in vehicle exhaust GHG emissions. However, these short-term benefits –called the operating phase impact- might be offset over the long-run by the induced demand generated by the travel-time reduction resulting from transportation improvements.

The positive economic impact in terms of savings in total vehicular delay and total network fuel consumption can affect other economic sectors in regional economies. Since these industrial sectors use transportation networks to deliver their goods and services, they will benefit from the savings in total congestion cost and can reinvest these savings to expand their businesses. In the long-term, this will lead to increases in the GHG emission due to production expansion and excessive use of transportation networks to deliver the extra goods and services. Despite the operating phase which only considers the direct impact of deploying congestion pricing on vehicle exhaust, this phase- called the secondary phase- concerns the extra emissions due to the induced activities in the industrial sectors enhanced by congestion pricing. This necessitates using an efficient assessment tool with the ability to model the long-term economic and environmental impacts at the economy-wide scale. Even though PARAMICS is a powerful tool to evaluate the short-term benefits of HOV/HOT lane deployment, it is not able to evaluate the potential long-term impacts of this transportation improvement. To address this, Leontief's input-output (I-O) model was chosen. The I-O model establishes the financial flow between different industrial sectors in the economy, usually during a year. By integrating the emission data associated with each economic sector into the I-O table, this model is able to evaluate the long-term environmental impact of any significant changes in the economic sectors. Since transportation is a separate economic sector in the I-O model, it can be utilized to assess the long-term environmental impact of HOV/HOT deployment.

To study the magnitude of both the operating and the secondary phase impacts of implementing a high occupancy toll (HOV/ HOT) shoulder lane on a 7.5 km section of Deerfoot Trail (Highway 2), Calgary is considered as a case study. The dynamic shoulder HOV/HOT lane algorithm was formulated to minimize the total passenger travel-time (TPT) on the motorway. The proposed HOV/HOT lane model was then evaluated to assess the potential savings in GHG emissions and total congestion cost. Finally, the impact of the secondary phase was evaluated using Leontief's input-output (I-O).

1.3 Objectives of Study

The goal of this study is to examine whether or not implementing the dynamic HOV/HOT shoulder lane is beneficial from an economic and environmental perspective.

To meet this goal, specific objectives are proposed as follows:

1) Develop a new HOV/HOT lane modeling approach aiming to minimize total passenger travel-time.
2) Conduct QUADSTONE PARAMICS microsimulation to investigate the operating phase impact of HOV/HOT lane implementation in Deerfoot Trail, Calgary, including savings in total congestion cost and total GHG emissions.
3) Evaluate the secondary phase impacts of implementing HOV/HOT lane in Deerfoot Trail using input-output analysis.

1.4 Organization of Thesis

This thesis consists of five chapters as follows:

Chapter Two Contains a literature survey on different methods of evaluating the environmental impacts of different techniques. Moreover, different approaches to modelling HOV/HOT lane are reviewed, including the model used for the optimization problem and optimum toll determination. Furthermore, studies of implementing input-output analysis in determining the economic and environmental impact are reviewed.

Chapter Three In this chapter, a description of the HOV/HOT lane implementation process is presented. First, the proposed model of the system-wide optimization problem is discussed. This minimization problem aims to determine the optimum traffic density of the HOV/HOT lane. Secondly, the optimum toll determination function is discussed in detail. Finally, a case study is conducted to evaluate the performance of the proposed HOV/HOT implementation model to reduce traffic congestion and GHG emissions.

Chapter Four In this chapter, an investigation of the secondary impact of transportation strategies is presented. The case study is then conducted to determine the secondary phase impact of implementing HOV/HOT lane in Deerfoot Trail, Calgary. Finally, a sensitivity analysis is performed to evaluate and compare the operating phase, secondary phase, and total impact of implementing the same transportation strategies in the City of Calgary and the City of Edmonton.

Chapter Five This chapter summarizes the major conclusions and recommendations from the studies in this thesis.

CHAPTER TWO: LITERATURE REVIEW

2.1 HOV/HOT Lane Implementation

2.1.1 Brief History of HOV/HOT Lane Implementation

Traffic congestion costs millions of dollars per year, including lost time, wasted fuel, and GHG emissions. Based on the Urban Mobility Report (2005), on average each traveler spent 47 hours in traffic congestion and paid $749 as congestion cost in the 85 surveyed areas. So, it is critical to manage and utilize the current traffic facilities, especially as expanding highway capacities becomes more difficult in metropolitan areas.

For several decades, implementing high occupancy vehicle (HOV) lanes was a feasible solution to decrease congestion costs by providing express lanes in congested highways for high occupancy vehicles. Since the early implementation of HOV lanes in the early 1970s, there has been a steady stream of reports on this topic. It was widely recognized that HOV facilities are able to carry more travelers than the general purpose (GP) lanes, especially during peak traffic hours. Kim et al. (2002) evaluated the potential impact of adding an extra HOV lane to an existing highway. They used QUADSTONE PARAMICS (an acronym for **para**llel **mic**roscopic **s**imulation) Monitor along with application programming interface (API) to model it. They found that implementing HOV lanes will improve travel time significantly. They also determined that PARAMICS model used in conjunction with API is an effective tool to model the traffic behavior in the freeway section with extra HOV lanes, and can be used to model the likely benefits of implementing HOV lanes.

However, there are some other studies that criticized the implementation of HOV lanes in favor of HOV/HOT lane deployment. Dahlgren (1997) showed that under some circumstances the HOV lanes are underutilized, especially when the general purpose lanes are highly congested. In this situation, single occupancy vehicles (SOV) waiting in a queue in the general purpose lanes cannot benefit from the existing underutilized capacity of the HOV lanes. While the desired traffic speed in the HOV lanes is the free flow speed, total freeway travel-time in the GP lanes will substantially increase. He also concluded that HOV lanes are superior to GP lanes only when there is a substantial difference between travel time in the HOV lanes and GP lanes, and the HOV lanes are well utilized, which requires both high traffic volume and a high proportion of HOVs.

Menendez and Daganzo (2007) proved that freeways with HOV lanes can accommodate fewer vehicles, which means that it may spread the queue more widely throughout the network. This is mainly the consequence of HOV underutilization, which results in significantly higher traffic density in the GP lanes. This can be quite deleterious if longer queues block busy off-ramps; thus, resulting in underutilized facilities and less efficiency. So, improperly facilitated HOV lanes can create bottlenecks that cause major problems. Similarly, Kwon and Varaiya (2005) indicated that the underutilized HOV lanes were found to increase traffic congestion and decrease traffic throughput by 400 vehicles per hour. Moreover, in their case study, 81% of the time, the HOV lanes were underutilized. They also found that the HOV lanes offer only a small reduction in travel time. More specifically, over a random 10 mile route section, the savings in travel time through using HOV lanes versus GP lanes was only 1.7 minutes. On the other hand, the HOV lanes were shown to be able to decrease the overall network traffic congestion only when the GP lanes were congested. In another study, Konishi and Mun (2010) showed that converting the HOV lanes to the HOV/HOT lanes can decrease the distortion from the difference in congestion level between different types of lanes. Thus, the concept of HOV/HOT lane was proposed as an attempt to overcome the limitations of HOV lanes. HOV/HOT lanes are able to mitigate congestion by allowing the SOV to use this lane by paying a toll when additional capacity exists in the HOV/HOT lane. Proper implementation of HOV/HOT lanes is reported to decrease the underutilization of the lanes during rush hours (Safirova et al., 2003).

2.1.2 HOV/HOT Lane Modelling

The first HOV/HOT lane was implemented on State Route 91 in Orange County, California, U.S. in 1995. After the first implementation, three other U.S. states, including Texas, Minnesota, and Colorado have implemented HOV/HOT lanes (Myron and Ungemah, 2006). Therefore, HOV/HOT lanes have been increasingly recognized in research and practice as a viable measure to improve traffic operation efficiency. Fig. 2.1 illustrates an example of a dynamic HOV/HOT lane.

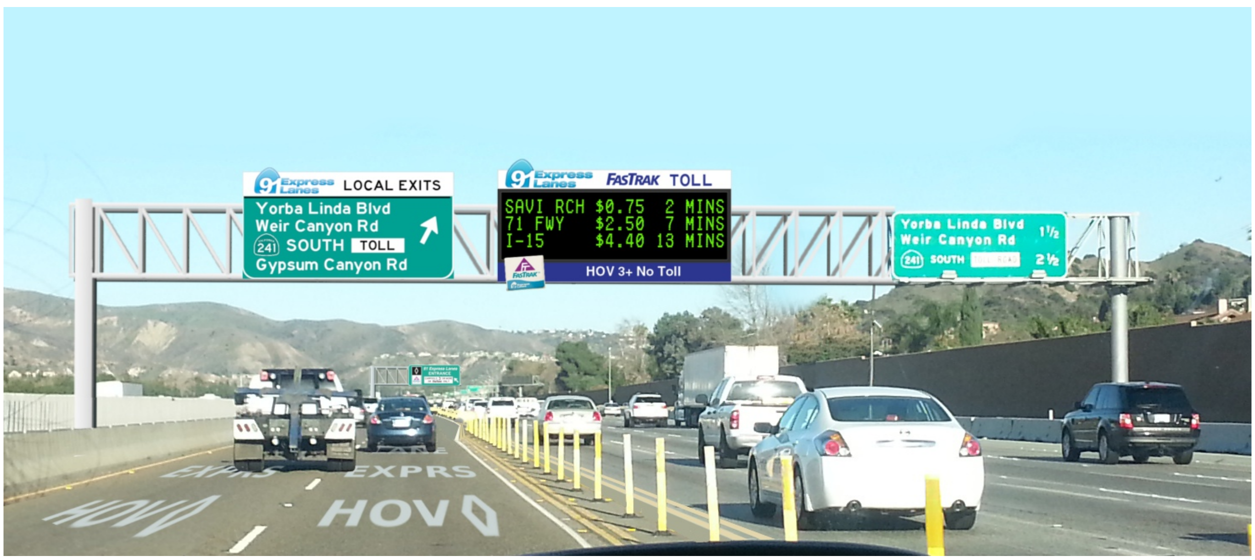

Figure 2. 1. HOV/HOT lane, State Route 91 in Orange County, California, U.S (http://ttcinlandempire.blogspot.ca/2013/11/exploring-91-express-lanes-access.html)

Each HOV/HOT model consists of two different functions. The first function is the traffic assignment model, which attempts to determine the traffic assigned to the HOV/HOT lane in order to optimize one or several key performance aspects of the transportation network. The second part of the HOV/HOT model is the driver's route choice model, which calculates the optimum toll rate of the HOV/HOT lane based on the traffic volume assigned to the HOV/HOT lane determined in the first function. Previous studies on HOV/HOT lane modelling can be classified based on the method that they used for the driver's route choice and toll determination model.

2.1.2.1 Traffic Assignment Model

The traffic volume assigned to the HOV/HOT lane can be determined by optimizing the performance of various functions. Cheng and Ishak (2012) proposed a new HOV/HOT modelling strategy for the managed lane on the I-95 U.S. state highway. They developed a dynamic toll pricing strategy that can assure a minimum level of service in the managed lanes and maximize the total toll revenue during peak traffic hours. In their proposed methodology, the optimum traffic volume in the HOV/HOT lane was determined, for which the total toll revenues expressed in equation (2. 1) is maximized:

$$\text{Maximize} \quad \hat{r}(t+1) = \hat{c}(t+1) \times \Delta\widehat{n_{in}}(t+1) \tag{2. 1}$$

Where:

$\hat{r}(t+1)$ – Estimated total toll revenue at time interval $(t+1)$ ($)

$\hat{c}(t+1)$ – Estimated feasible toll rate at time interval $(t+1)$ ($)

$\Delta\widehat{n_{in}}(t+1)$–Expected number of vehicles entering the HOV/HOT lane at time interval $(t+1)$

In equation (2. 1), the total number of vehicles entering the HOV/HOT can be expressed as equation (2. 2):

$$\Delta\widehat{n_{in}}(t+1) = \widehat{N}(t+1) \times \sum_{j=1}^{n}\left[\widehat{P}(j, t+1) \times q(j)\right] \tag{2. 2}$$

Where:

$\widehat{P}(j, t+1)$ – The probability of choosing the HOV/HOT lane for drivers in income category j at time interval $(t+1)$

$\widehat{N}(t+1)$ – Total number of vehicles making a decision to choose between HOV/HOT and GP lanes in time interval $(t+1)$

$q(j)$ – The percentage of drivers in income category j

Similarly, Yang et al. (2012) determined the optimum traffic flow entering the HOV/HOT lane by maximizing the total toll revenue in each time step subject to maintaining the HOV/HOT lane average speed at the free flow speed. Considering the logit model, they proposed the optimization problem expressed in equation (2. 3) to maximize the toll revenue between time T_0 to time T:

$$\max \quad E\left[\sum_{n=1}^{N}\left(\int_{T_0}^{T}\sum_{m\in\Phi} D_n^m(t)p_n^m(t)dt\right)\right] \tag{2. 3}$$

Where:

$D_n^m(t)$ – The logit model of the motorway section between the n^th^ entrance and m^th^ exit in $[T_0, T]$ time interval

$p_n^m(t)$ – The proportion of drivers who choose HOV/HOT in the route section between the n^th^ entrance and m^th^ exit in $[T_0, T]$ time interval

The objective function is then modeled and solved using Markov decision process modeling.

In two similar studies, Coffee and Lain (2009) and Dawson et al. (2008) set their objective to provide free flow speed in the tolled lane. However, because they do not address the maximum capacity usage of the HOV/HOT lane, the existing capacity of the HOV/HOT lanes might be underutilized.

To prevent the underutilization of the HOV/HOT lane, Fu and Kulkarni (2013) set their objective function, such that the throughput of the HOV/HOT lane is maximized (while providing free flow speed in the HOV/HOT lane). The objective of their traffic assignment model was to regulate the HOV/HOT lane density at the target value, which is simply the critical density subtracted by a small allowance. The desired maximum traffic flow of the HOV/HOT lane is then calculated using the traffic fundamental relationship expressed in equation (2. 4):

$$q_d = k_d \times v_c \tag{2. 4}$$

Where:

q_d – Desired input traffic volume to the HOV/HOT lane (vehicle/hour)

k_d – Target density (critical density) (vehicle/km)

v_c – Traffic flow speed (km/hour)

Taking a similar approach, Yin and Lou (2009) also tried to set the desired traffic density of the HOT lane as the critical density (corresponding to the maximum traffic flow). In the real world, this approach is also taken. For example, the Express Lanes in the 95 Express Project, as the first variable tolling project in the state of Florida, is established to safely operate at a free flow condition while maximizing throughput. In another instance, Robbins et al. (2009), in the Washington State Route 167 HOT lane pilot project, found that the HOT lane speed is required to be higher than 45 mph (Wang and Zhang, 2009).

In another study, Zhang et al. (2008) proposed a feedback control to maintain the free flow condition in the HOV/HOT lane. They partitioned three manipulation zones in the HOV/HOT lane based on their robustness: The first zone is where the speed in the lane is greater than 50 mph, which shows that sufficient capacity is available in the HOV/HOT lane so that the toll rate needs to be decreased to absorb more vehicles and prevent the underutilization of the existing extra capacity. The second zone is where the speed in the lane is between 45 mph and 50 mph, which indicates that the traffic density is close to the critical density, and the toll rate should be maintained at the current level. The third zone is where the speed in the HOV/HOT lane is less than 45 mph, which shows the overutilization of the express lane and the toll rate should be decreased fast to keep the density near the critical density.

While this method is able to fully utilize the available capacity of the HOV/HOT lane, small shockwaves in the HOV/HOT lane can significantly affect the capacity of the HOV/HOT lanes which are operating at the critical traffic states and can lead to significant drops in capacity.

To address this problem, Lou et al. (2011), developed a multi-objective function to maximize the throughput in each section of the freeway and keep the traffic density in the HOV/HOT lane less than the critical density simultaneously. In their proposed method, the motorway was split into different cells, as shown in Fig. 2.2. Moreover, the optimum traffic flow in the HOV/HOT lane is determined based on rolling horizon at each time step for each cell by solving the multi-objective optimization problem expressed in equation (2. 5).

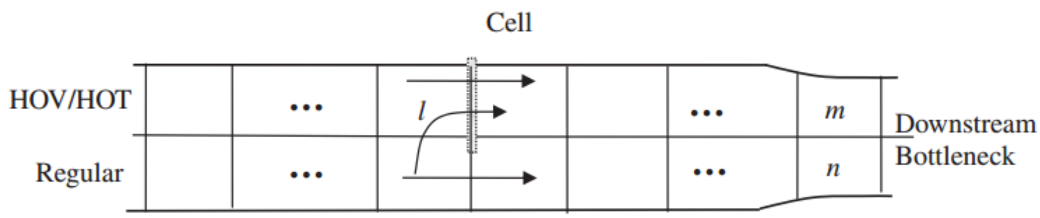

Figure 2. 2. Part of roadway split into cells (source: Lou et al. 2011)

$$\max \quad \left\{ \sum_{j=t+1}^{t+M} [q_m(j) + q_n(j)] + \theta . \min\left[\tilde{k} - \frac{1}{M} \sum_{j=t+1}^{t+M} k_1(j) , 0 \right] \right\} \qquad (2.\ 5)$$

Subject to $$0 \leq \beta \leq \beta_{max} \quad (2.6)$$

Where:

$q_m(j)$ – Traffic flow of the cell number m in the HOV/HOT lane at time step j (vehicle/hour)

$q_n(j)$ – Traffic flow of the cell number n in the GP lane at time step j (vehicle/hour)

$\tilde{k}$ – Critical density of the HOV/HOT lane (vehicle/km)

θ – Penalty parameter

$k_1(j)$ – Traffic density of the HOV/HOT lane at time step j (vehicle/km)

β_{max} – Maximum possible toll rate ($)

Although the goal was to reduce the weight of maximizing the traffic flow, i.e., keeping the traffic density close to the critical density, the optimum traffic flow of the HOT lane is still close enough to the maximum flow. This may cause the traffic state in the HOT lane to become unstable, especially in the case of the occurrence of shockwaves.

While most of the recent studies focus on improving the traffic flow in the HOT lane by maximizing the throughput while keeping the free flow condition, they neglect the traffic state in the GP lanes. In addition, none of them have dealt with the congestion reduction directly. Thus, these strategies are not able to maximize congestion reduction. To address both issues in this study, minimizing total passenger travel-time in both HOV/HOT and GP lanes was chosen as the main objective of this study to minimize the negative impacts of congestion, such as delayed time, wasted fuel, and excessive GHG emissions due to traffic congestion.

2.1.2.2 Toll Determination Model

After identifying the optimum traffic flow assigned to the HOV/HOT lane, the toll rate needs to be calculated for each time step of the HOV/HOT lane operation period. Different methods and functions have been offered to achieve this. One of the most popular methods is determining the toll rate using the Logit model expressed in the general form in equation (2. 7):

$$F_{HOT} = F_{GP} \times \frac{\exp(U_{HOT})}{\exp(U_{HOT}) + \exp(U_{GP})} \tag{2. 7}$$

Where:

F_{HOT} – Traffic flow approaching the HOV/HOT lane (vehicle/hour)

F_{GP} – Traffic flow approaching the general purpose lanes (vehicle/hour)

U_{HOT} – Utility of choosing HOV/HOT lane

U_{GP} – Utility of choosing general purpose lanes

Different versions of the Logit model with different utility functions for the HOV/HOT and GP lanes have been considered in previous studies. For example, Cheng and Ishak (2013) considered a Logit model as expressed in equation (2. 8):

$$P(i,t) = \frac{e^{U_m(i,t)}}{e^{U_m(i,t)} + e^{U_g(i,t)}} = \frac{1}{1 + e^{-\Delta U(i,t)}} \tag{2. 8}$$

Where:

$P(i,t)$ – The probability of choosing managed lane for driver i at time interval t

$U_m(i,t)$ – Utility of choosing managed lane for driver i at time interval t

$U_g(i,t)$ – Utility of choosing managed lane for driver i at time interval t

$\Delta U(i,t) = U_m(i,t) - U_g(i,t)$ – The difference between the utility of choosing the managed lanes and the GP lanes for driver i at time interval t

They expressed the utility of choosing the managed lane as a function of the toll rate and the total travel-time in the managed lane, while the utility of choosing GP lane was expressed as a function of the travel time in the GP lane, as shown in equation (2. 9) and (2. 10):

$$U_m(i,t) = -\alpha(i) \times c(t) - \beta(i) \times T_m(t) \tag{2. 9}$$

$$U_g(i,t) = -\beta(i) \times T_g(t) \tag{2. 10}$$

Where:

$\alpha(i)$ – Rate of change of utility for driver i per unit change of toll rate

$c(t)$ – The toll rate in the managed lane at time interval t ($)

$\beta(i)$ – Rate of change of utility for driver i per unit change of travel-time savings (value of time) ($)

$T_m(t)$ – Travel time in the managed lane at time interval t (hour)

$T_g(t)$ – Travel time in the GP lane at time interval t (hour)

In the above equation, the values for $\alpha(i)$ and $\beta(i)$ are user-specific and vary from region to region. In this study, the value for $\alpha(i)$ is assumed to be one, while the value of $\beta(i)$ is considered to be 90% of drivers' mean hourly income. In another study, Chand et al. (2012) evaluated the value of time for travelers on Houston's Katy freeway by conducting three different survey techniques. They found that the values for $\beta(i) = 0.5$ can be estimated as 63%, 108%, and 132% of the mean hourly income rate of the chosen samples.

Adopting the same Logit model, Yin and Lou (2009) assumed that $\alpha(i) = 1$ and $\beta(i) = 0.5$. They also added two extra parameters to the utility functions to model the route choice of the travelers when the travel time in both HOV/HOT and GP lanes are the same and the toll rate is zero:

$$U_m(i,t) = -\alpha(i) \times c(t) - \beta(i) \times T_m(t) + \gamma^m \tag{2. 11}$$

$$U_g(i,t) = -\beta(i) \times T_g(t) + \gamma^g \tag{2. 12}$$

Where γ^m and γ^g represent the drivers' fixed preference between the two lanes. When travel time of taking both GP and HOV/HOT lanes is the same and the toll rate is zero, drivers may have different preferences because of the road conditions and lane capacity. The difference between γ^{m} and γ^{g} represents this preference.

In another study, Zhang et al. (2008) determined the toll rate assigned to the HOT lane using the same logit model as was shown in equation (2. 8), but employing different utility functions as expressed in equations (2. 13) and (2. 14):

$$U_{HOT} = \frac{1}{TC_{HOT}} = \frac{1}{\alpha \times TT_{HOT} + TR_{HOT}} \tag{2. 13}$$

$$U_{GP} = \frac{1}{TC_{GP}} = \frac{1}{\alpha \times TT_{GP}} \tag{2. 14}$$

Where:

U_{HOT} – The utility of choosing HOT lane

U_{GP} – The utility of choosing GP lanes

TC_{HOT} – Total cost of choosing HOT lane ($)

TT_{HOT} – Total average travel-time of HOT lane (hour)

TR_{HOT} – Toll rate of HOT lane ($)

TC_{GP} – Total cost of choosing GP lanes ($)

TT_{GP} – Total average travel-time of GP lanes (hour)

α – Value of time ($)

They adopted a feedback control to calculate the HOV/HOT lane share of total traffic flow at time step $(t + 1)$ -$P_{HOT}(t + 1)$- from the previous flow share of the HOV/HOT lane. After identifying the HOV/HOT share of traffic volume at each time step, the optimum toll rate can be calculated using equation (2. 8).

Taking a different approach, Fu and Kulkarni (2013) modeled the driver decision by a discrete choice model shown as equation (2. 15):

$$P = 1 - F\left(\frac{t_r}{TT_{GP} - TT_{HOT}}\right) \qquad (2.\ 15)$$

Where:

P – Proportion of vehicles

t_r – Toll rate ($)

TT_{GP} – Travelling time in the GP lane (hour)

TT_{HOT} – Travelling time in the HOV/HOT lane (hour)

$F(.)$ – Cumulative distribution of the percentage of drivers with a particular value of time (VOT)

The dynamic pricing algorithm of the HOV/HOT lane implemented in the 95 Express Project, Florida, calculates the toll rate every 15 minutes based on the level of service observed in the HOV/HOT and the difference between the traffic densities measured in the previous and the current time step. In their method, for a traffic density of 27 or higher, for every unit of increase in the traffic density, the toll rate increases $0.25. The minimum amount of the toll is $0.25 and the maximum toll rate value is $6.20. Table 2.1 shows the minimum and maximum toll rates associated with each level of service.

Table 2. 1. Toll rate associated different level of service for 95 Express Project, Florida (source: Rodriguez et al. 2009)

Level of service	Traffic density	Toll rate ($)	
		Minimum	Maximum
A	0-11	0.25	0.25
B	11-18	0.25	1.50
C	18-26	1.50	3.00
D	26-35	3.00	3.75
E	35-45	3.75	5.00
F	>45	5.00	6.20

In a recent study, Sinprasertkool et al. (2011) developed a model called TPM. This model extends the Wardrop's first principle (Wardrop, 1952) to a user equilibrium concept in the context of managed lanes versus the general purpose lanes. This model is expressed in equation (2. 16) as follows:

$$\mathrm{CTS} = \frac{\mathrm{T}}{[(\mathrm{L}_{\mathrm{GPL}} \times \mathrm{t}_{\mathrm{GPL}}) - (\mathrm{L}_{\mathrm{ML}} \times \mathrm{t}_{\mathrm{ML}})]/\mathrm{L}_{\mathrm{ML}}} \tag{2. 16}$$

Where:

CTS- The cost of time saving ($)

T– Toll rate ($)

$\mathrm{L}_{\mathrm{GPL}}$ – Corridor length of general purpose lanes (km)

L_{ML} – Corridor length of managed lanes (km)

$\mathrm{t}_{\mathrm{GPL}}$ – Travel time in general purpose lanes (hour)

t_{ML} – Travel-time length in managed lanes (hour)

Based on this model, the user equilibrium is achieved when the CTS and the value of time (VOT) is equal. Due to simplicity and easy application to real world problems, this approach was taken in other studies, e.g., (Olyai and Ardekani, 2013), as well as the current study.

2.2 Methods of Determining the Environmental Impact of Transportation Improvements

While the impact of transportation system improvement strategies on traffic congestion has long been a topic that is intensively examined in the literature, the environmental impact of these transportation strategies has not yet been adequately investigated. There is a wide range of tools, methods, and software that can be utilized to evaluate the environmental impacts of transportation improvement strategies. One common method is determination of the impact based on collected field data. Song et al. (2013) used emission data collected by a vehicle with a portable emission measurement system (PEMS) to compare the emissions and fuel consumption for an ecological route and a time-priority route. Instead of obtaining the emission factors from a macrosimulation emission model, e.g., VT-Micro model and CMEM, or a microsimulation emission model, e.g., MOBILE6 and EMFAC, they used the emission factors data collected by a vehicle with PEMS operated on regular routes in the Beijing urban area under different driving conditions. They showed that operating a vehicle in the ecological route should reduce CO_2 emissions and fuel consumption by 13.5%.

Weng et al. (2013) collected speed characteristics of over 2,000 vehicles at various electronic toll collection (ETC) and manual toll collection (MTC) lanes in Beijing and different types of toll plazas, including the main line toll station and ramp line toll station. They classified these 2,000 vehicles into seven different types of vehicles based on body type and fuel consumption rate. They then conducted laboratory experiments for each of the seven different types of vehicles using a vehicle emission testing system (VETS) to evaluate the exhaust emission of vehicles operating in ETC and MTC lanes. They demonstrated that using ETC, instead of MTC, in Beijing is expected to save 4.74 million liters of gasoline and reduce vehicle emissions by 844.8 tonnes of CO_2 eq. per year.

In a similar study, Song et al. (2008) evaluated the exhaust emissions of the Volkswagen Jetta in Beijing for both ETC and MTC lanes. The vehicle passed 48 times through tollbooths, and emission data were collected by PEMS. Their analysis showed that the NOx, HC, and CO emissions of the ETC lanes were 16.4%, 71.2%, and 71.3% less than those of the MTC lanes, respectively.

In another study, Hernández et al. (2013) showed that implementing open road tolling (ORT) can save 4,400 tonnes of CO2 emission of their case study per year. Field data collection was carried out in order to determine the traffic patterns and distribution of the use of toll booths. They then applied the collected field data in the following mechanical model to obtain the energy consumption of the vehicles using the toll booths:

$$U_k = \left[C_i \times M_{fr} \times a \times d_i + C_r \times P \times \cos\theta \times d_r + \left(1/2\right) \times \rho \times C_d \times A_f \times v_r^2 \times d_a\right] \times \left(1/\eta_{motor}\right) \times e_v \tag{2. 17}$$

Where:

U_k- Total energy consumption (mega-joules per vehicle)

C_i- Mass transfer coefficient correction factor

M_{fr} - The rotational mass of the vehicle (kg)

α - The rate of acceleration or deceleration (m/s^2)

C_r - The rolling resistance

P - Vehicle weight (kg×m/s^2)

θ - Road gradient (m/m)

ρ- Air density (1,225 kg/m^3)

C_d - Drag resistance

A_f - Frontal area of the vehicle (m^2)

v_r - Relative velocity of the vehicle (m/s)

d_a – Effective aerodynamic distances traveled (m)

η_{motor} - Efficiency of the engine

e_v - Wind exposure factor

Finally, by using the appropriate emission factors, the GHG emission associated with the total energy consumption is calculated.

While collecting field data can provide invaluable emission data of the operating phase of deployed strategies, it is unable to predict the impacts of transportation improvement strategies that have not yet been implemented. Therefore, this method is not suitable for the planning phase.

One of the other most popular methods to assess the environmental impact of transportation improvements is using microsimulation. Armstrong and Khan (2006) evaluated GHG reduction for various transportation strategies using INTEGRATION, which is a trip-based microscopic simulation model that simulates the behavior of each driver-vehicle unit at a resolution of one deci-second- for a region in the City of Ottawa. They obtained traffic count data extracted from the City of Ottawa traffic count database and imported them along with other travel inputs into QueensOD which is a model for estimating origin-destination demands based on observed link traffic flow.

Four different intelligent transportation system (ITS) techniques along with two none ITS strategies were evaluated in terms of the GHG emission saving. According to Transport Canada (2003), ITS refers to the integrated application of information processing, communications, and sensor technologies, to transportation infrastructure and operations. These systems bring together users, vehicles and infrastructure into a dynamic relationship of information exchange, resulting in better management strategies and more efficient use of available resources.

The measures of effectiveness for each scenario were compared with “existing” conditions for two baseline scenarios, one with no traffic incidents, and the other assuming a 20-minute collision. The ability of each scenario to reduce GHG emissions within the study area is summarized in Table 2.2. They also found that in the short-term, ITS techniques could reduce GHG emissions from the study area transportation network by 20%.

Table 2. 2. % GHG emission reduction in the City of Ottawa for various transportation strategies (source: Armstrong and Khan, 2006)

Scenario	% Change in GHG emissions relative to the base case	
	No incident	With incident
Variable message signs	-2%	_
Traveler information/navigation	-4%	_
Toll collection	-1%	_
Incident management	_	-3%
Reduced demand	-31%	_
New capacity	-3%	_

Using PARAMICS, Bartin et al. (2007) demonstrated that, in the long-term, the extra emissions caused by induced demand could overcome emission reduction from converting toll plazas on the New Jersey Turnpike into ETC.

They used three datasets as the model traffic inputs as follows:

1. Vehicle transaction data for July 27, 2005 which included vehicle-by-vehicle entry and exit time.
2. Daily OD demand data for June 30, 1999 which represented a typical weekday before the ETC implementation.
3. Video recording of the exit and entry plazas on April 28, 2006. Entry and exit toll processing times are extracted from this dataset.

They obtained corresponding emission factors for various vehicle types from a microsimulation emission model called MOBILE6.2. Emission factors given by MOBILE6.2 were used in a PARAMICS emission plugin called QUADSTONE PARAMICS Monitor to estimate vehicle emissions at each time step.

To evaluate the short-term impact of deploying ETC, they compared the simulation results for the 1999 network before and after ETC implementation. The results in the short-term showed that ETC deployment is able to reduce CO, HC and NO_x emissions by 36.3%, 47.2% and 28.2%, respectively, while increase PM_{10} emissions by 6.7%. For the long-term, they compared air pollution levels of the 1999 network before deploying ETC and the 2005 network after ETC deployment. The simulation results showed that CO and HC emissions reduced by 12% and 20%, respectively. However, NOx and PM10 emission levels increased by 20% and 96%, respectively. It is worth mentioning that, in the long-term, the air pollution level for the mainline links are substantially increased. To fully evaluate the effect of ETC deployment in the long-term, the authors considered another scenario to compare emissions level of the 1999 and 2005 networks without ETC implementation. This time, they showed that CO, HC, NO_x and PM_{10} emissions increased by 10.1%, 11.2%, 3.4% and 13%, respectively, at toll plazas. Moreover, they demonstrated that without ETC deployment, the 2005 network cannot handle current traffic demand.

Using a macroscopic traffic flow simulation called S-model, Lin et al. (2010) showed that deployment of model predictive control (MPC) can reduce CO, CO_2, NO_x and HC emissions by 36%, 17%, 21% and 20%, respectively. They determined the GHG emissions of each time step during the simulation using VT-Micro, which is a microscopic dynamic-based traffic emission and fuel consumption model. It evaluates the emissions based not only on the speed of every vehicle, but also the acceleration or deceleration of each vehicle. This traffic emissions model is also able to calculate the vehicle's emissions and fuel consumptions even when a vehicle stops at the stop line or starts up to leave from the stop line.

In another study, Zegeye et al. (2009) showed that deploying a variable speed limit model on 12 km of a two-lane road would decrease both fuel consumption and CO_2 emissions by 14.15%. They integrate the macroscopic traffic flow model METANET (Messmer and Papageorgiou, 1990) with the microscopic emission model VT-Micro (Ahn et al., 1999) to obtain better estimates and predictions of the emissions of the traffic flow. METANET is a macroscopic traffic model that describes the average behavior of vehicles in a traffic network. In this modeling technique, a link is divided into a number of segments where the traffic behavior in each segment is described by a set of dynamic equations. This model is also deployed in this thesis to predict the future state of traffic demand.

While macroscopic traffic models are easier to model and calibrate compared to their microscopic counterparts, Sbayti et al. (2002) showed that macroscopic analysis underestimates emissions by as much as 27% compared to microscopic analysis.

It is to be noted that the majority of the above-reviewed literature examined the impact of transportation improvements in the operating phase assuming a fixed demand, which is likely to result in the overstating of travel-time savings, energy-use consumption, and GHG emissions. Considering the limitations of the collecting field data approach and relatively inaccurate emission estimation resulting from macrosimulation models, a microsimulation model is chosen in this study to model both the traffic state and transportation network emissions using QUADSTONE PARAMICS microsimulation software. As mentioned previously, this approach is considered to determine the operating phase impact of implementing HOV/HOT lanes.

2.3 Lifecycle Assessment (LCA) and Input-Output analysis

Lifecycle assessment is a technique to evaluate the environmental impact associated with the life time of a product from cradle to grave, including the impact from extracting raw materials, production operations and manufacturing, transportation, distribution, use, repair, and disposal.

Generally, there are two different methods for conducting LCA:

- Process-based LCA:

A process-based LCA requires mapping the entire life-cycle of the product, including raw material extraction and processing, manufacturing, transportation, use, and recycling or disposal. The LCA GHG emissions will be the sum of the GHG emissions associated with each step. Many studies have been conducted using this kind of LCA in the field of transportation.

- Economic Input-Output LCA (EIO LCA):

Economic Input-Output life-cycle assessment involves aggregated level of economic data to quantify the environmental impact of any significant change in the economy. This model first was introduced by Leontief (1970) based on his economic Input-Output model first introduced in the 1930s (Leontief, 1936). In the mid-1990s, Hendrickson et al. (1998) developed the EIO LCA model to assess the economy-wide environmental impact of a product or a process.

They showed that the environmental impact of a certain amount of economic output can be calculated using equation (2. 18):

$$B_i = R_i \times X = R_i(I - D)^{-1}F \qquad (2.\ 18)$$

Where:

B_i – Vector of environmental output representing burden of type i

R_i – Environmental impact per dollar of output for each process

X– Total suppliers input

I – Identity matrix

D– Requirement matrix

F – Desired final demand

In equation (2. 18), for different amount of desired demand, the associated GHG emissions can be calculated.

While LCA has been widely utilized to evaluate the environmental impact of numerous physical products and processes, few studies have considered it to evaluate the environmental impact associated with policies and strategies. This is quite evident when it comes to the transportation context. There are many studies that focus on assessing the environmental impact associated with materials and processes in transportation considering the process-based LCA. For example, Bachmann et al. (2014) compared the life-cycle emission of hybrid trucks and conventional diesel trucks considering three distinct phases:

- Well-to-tank (diesel production)
- Tank to wheel (vehicle operation)
- Vehicle cycle (manufacture to disposal)

Focusing on transportation infrastructure, Deng et al. (2014) assessed the life-cycle emission of concrete pavement construction by evaluating the environmental impact of different inventories, including raw materials production, material transportation, pavement surfacing, and upstream processes. Hanson et al. (2014) evaluated life-cycle emissions of commuter rail projects concentrating mainly on the construction steps.

Taking the impact of traffic delay into consideration, Huang et al. (2009) examined how shutting down a road section within a construction zone can affect total life-cycle GHG emissions of the constructed pavement. A process-based LCA was implemented to evaluate GHG emissions of the pavement construction, and microsimulation was used to assess GHG emissions due to the traffic congestion caused by pavement construction in the construction zone. It was found that the environmental impact of traffic congestion is far more detrimental in terms of CO_2 emissions than construction.

In a similar study, Kang et al. (2014) evaluated the GHG emissions of 7.6 reconstruction projects done in the I-90 state highway. They assessed the GHG emissions associated with material production, construction, and GHG emissions due to the traffic delay in the construction zone. Interestingly, they found that traffic delay is responsible for 0.5 %-2.3 % of total life-cycle GHG emissions of the project, which is fairly close to the GHG emissions of the construction phase (2.8 %-2.9 %).

While process-based LCA provides invaluable information about the GHG emissions associated with each life stage of a product, tracking all of the indirect contributions would be impossible in a process-based LC, because cycles among the stages would continue indefinitely. Indeed, due to the existence of numerous processes involved in the life stage of a product, in the case of missing data or processes, the final environmental impact will be underestimated. Moreover, since companies are frequently reluctant to reveal information about the whole process to maintain their competitive edge, the validity of the released information is doubtful.

EIO LCA is a powerful tool that can address these limitations by considering the environmental impact of both direct and indirect contributors to GHG emissions. Similar to process-based LCA, EIO LCA has been widely used to assess the environmental impact of physical products or processes. Hendrickson and Horvath (2007) deployed the I-O model to evaluate life-cycle RCRA Subtitle C hazardous wastes and toxic release inventory (TRI) emissions of $1000 of steel-reinforced concrete product. Instead of using the usual process-based life-cycle assessment (LCA), they use I-O analysis to catch the impact on the entire economy. Hawkins et al. (2007) combined the economic I-O model with the material flow analysis model to better estimate total lead and cadmium as toxic metals, release from producing $10 million additional final demand in each economic sectors. Joshi (1999) evaluated the LCA environmental impact of steel and plastic fuel tank systems for automobiles in terms of conventional pollutant emissions and toxic release to the environment.

However, considering the transportation context, few studies have dealt with the economic and environmental impact of transportation strategies and techniques using the I-O technique. As a pioneering work, Farooq et al. (2008) assessed the economic impact of implementing intelligent transportation system (ITS) in Michigan using I-O analysis. They established a framework to adopt the total congestion cost-savings enhanced by full ITS implementation into the Michigan I-O table reconstructed from the national I-O table. They assumed that ITS deployment will affect mostly the manufacturing sector in the regional economy and assessed the impact of congestion cost-savings on this economic sector. However, it seems that manufacturing is not the only economic sector that can be affected by congestion cost-saving. Since other economic sectors in regional economies use transportation networks to deliver their goods and services, they can also benefit from the travel time due to less congested roads and freeways. This necessitates a new approach able to model the impact of savings in the total congestion cost on all of the economic sectors in regional economies. Moreover, as discussed previously in this section, there is a huge gap in evaluating the environmental impact of transportation strategies using EIO LCA. So, this study is going to use EIO LCA to determine the potential impact of implementing transportation strategies at the regional level. Considering the impact on the regional level, the system boundary is the transportation network and other economic sectors at the city level.

CHAPTER THREE:FRAMEWORK FOR THE PROBE-BASED HOV/HOT LANE IMPLEMENTATION APPROACH

This chapter describes the algorithm developed for implementation of high occupancy toll (HOV/HOT) temporary shoulder use. The ability of this model to predict the future traffic state, based on current traffic conditions, enables the HOV/HOT lane system to not only detect and respond proactively to any anticipated variation in traffic demand entering the mainline, but also controls the traffic flow entering the HOV/HOT and GP lanes by adjusting the appropriate toll rates.

The main inputs of this HOV/HOT lane model are the space mean speed (SMS) and the vehicle count data, which are assumed to be provided continuously from the probe vehicles and point detectors, respectively. These two sources of sensor information are complementary to each other and can provide reliable estimates of traffic state. Aggregated travel-time data provided from vehicle probes might be obtained from various sources, such as Bluetooth data, INRIX data derived from GPS enabled devices and, in the future, Connected Vehicles. As travel time is the inverse of speed, proven vehicle data can provide direct estimates of space mean speed (SMS). Unlike traffic flow measurement, SMS is a reliable indicator of congestion. Section SMS data and traffic flow from point detectors are used to estimate vehicle density based on the fundamental flow relationship and are also employed in the traffic state prediction step. This information is then fed to the HOV/HOT lane algorithm, which consists of a single objective function that attempts to minimize the total passenger travel-time (TPT) in the mainline over a certain horizon.

A traffic prediction model is adopted based on the METANET model (Messmer and Papageorgiou, 1990) to predict the traffic condition in the future horizon of time, which is one minute in this model. The PARAMICS microsimulation software was chosen as it is capable to model the details of the case study precisely and able to provide valuable GHG emission data of HOV/HOT lane system implementation. The emission data, including CO_2, CO, NO2, and CH_4 can be obtained by running PARAMICS Monitor plugin during each simulation run.

3.1 Overview of Applied Framework for HOV/HOT Lane Implementation

To calculate traffic density based on the received SMS and traffic count data, the mainline link is divided into several segments. In PARAMICS, each route consists of many links. Links are the routes between two successive nodes in the transportation network with a certain number of lanes. A group of consecutive links with the same number of lanes creates a segment. Since the traffic volume of the mainline link changes frequently at on-ramps and off-ramps, to have consistent traffic flow on each segment, no on-ramps or off-ramps must be located at the middle of each segment. This means that the segments should be selected considering the location of off-ramps and on-ramps. For example, the proposed scheme of segments is shown for a motorway in Fig. 3.1.

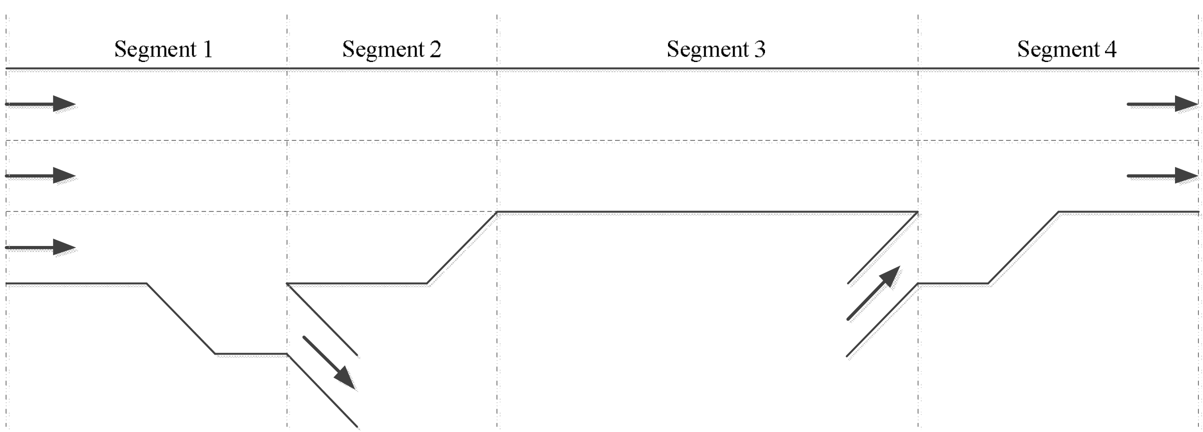

Figure 3. 1. Freeway section with four segments

In this study, the average speed of probe vehicles in each segment was obtained every three seconds (Lu et al., 2013). In addition, as shown in Fig. 3.1, one point detector is installed at each motorway section to enable the model to determine the traffic volume data for each section during each time interval.

Fig. 3.2 illustrates the framework which is followed in this study to determine the optimum motorway toll rate for each 60-second time interval of simulation.

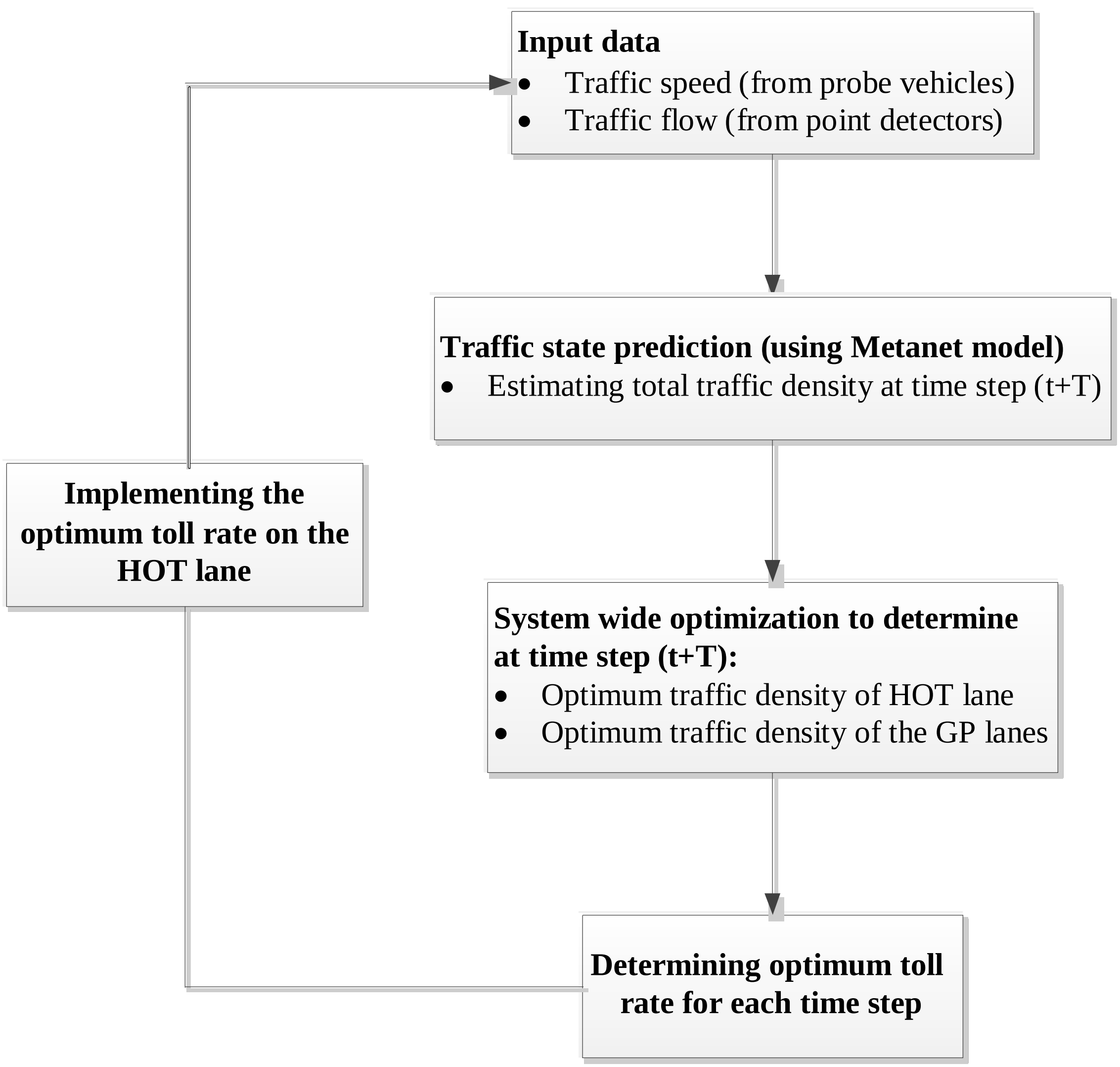

Figure 3. 2. Framework of HOV/HOT lane implementation

As can be seen, the framework consists of:

1) Data collection

2) Traffic state prediction

3) Transportation network optimization

4) Toll determination and implementation

The proposed HOV/HOT lane implementation strategy takes SMS as average speed and traffic volume extracted directly from probe vehicles commuting on different sections of the motorway and point detectors, respectively. The fundamental traffic flow relationship is used to convert the SMS and traffic flow to vehicle density in each section as required for the traffic prediction steps. Finally, by minimizing the objective function, the optimum toll rate is implemented in the HOV/HOT lane each minute.

In the following section, the details of deploying the proposed HOV/HOT lane strategy are explained step by step as related to data collection, traffic condition prediction, system-wide optimization, and toll rate determination and implementation.

3.1.1 Data Collection

Since the developed HOV/HOT lane strategy aims to implement the optimum toll rate of the HOV/HOT lane each minute, the dynamics of the transportation system -including the traffic demand of the mainline link and the inflow and outflow from on-ramps and off-ramps, respectively- need to be captured at each time step. This way, the HOV/HOT lane control can respond in real time.

The main input data required to be fed into the system-wide objective function are the total vehicle density existing on each motorway segment at each time step. Since the Newell's triangular macroscopic traffic model (Newell, 1993) is chosen to determine the total density of each section, two variables need to be determined each time step:

1) Average motorway space mean speed (μ) :

The vehicles SMS extracted from probe vehicles are adopted as average vehicle speed in Newell's triangular model

2) Traffic volume (q) :

Vehicles count data at each time step extracted from point detectors located at the start point of each motorway section and also the detectors on the on-ramps and off-ramps near each section are used to determine the traffic flow entering each segment of the motorway.

The relationship between traffic density (k), average speed (v), and traffic volume (q) can be expressed from the fundamental traffic flow relationship as illustrated in equation (3.1):

$$k_i(t) = \frac{q_i(t)}{\mu_i(t)} \qquad (3.\ 1)$$

Where:

$k_i(t)$ - Traffic density of section i at time step t (vehicle/km)

$q_i(t)$ - Traffic flow of section i at time step t (vehicle/hour)

$\mu_i(t)$ - Traffic speed of section i at time step t (km/hour)

Using equation (3.1), traffic density can be determined to be fed into the next step.

3.1.2 Traffic State Prediction

Once the traffic density of section i at time step t is determined, the traffic condition can be predicted. The density of segment i at time step $(t + 1)$ can be calculated based on the law of conservation of vehicles. Based on this law, the density of segment i at time step $(t + 1)$ is equal to the current density of the segment i plus the traffic volume entering the segment minus the outflow traffic (Messmer and Papageorgiou, 1990):

$$k_i(t + 1) = k_i(t) + \frac{T_f}{L_i\lambda_i}[q_{i-1}(t) - q_i(t)] \qquad (3.\ 2)$$

Where:

$k_i(t + 1)$ - Traffic density of section i at time step $t + 1$ (vehicle/km)

$k_i(t)$ - Traffic density of section i at time step t (vehicle/km)

T_f - The time step used for the simulation of the traffic flow (hour)

L_i - The length of section i (km)

λ_i - Number of lanes of section i

$q_{i-1}(t)$ - Traffic flow of section $i-1$ at time step t (vehicle/hour)

$q_i(t)$ - Traffic flow of section i at time step t (vehicle/hour)

A typical value for T_f is 10 seconds (Messmer and Papageorgiou, 1990). This value should be selected such that T_f is smaller than the time it takes a vehicle driving at maximum speed to cross segment i. Since the time interval during which the toll rate is updated based on the current traffic state is 60 seconds, depending on the length of each segment, several iterations of calculating equation (3. 2) needs to be done to predict the traffic state at the end of each 60-second time interval. For example, if T_f is considered as 6 seconds, 10 iterations have to be conducted to estimate the traffic density at the end of each 60 seconds of simulation time interval. The series of time horizons for which the traffic density is predicted are: $t+1, t+2, \ldots, t+T$. The output of this step, i.e., $k_i(t+T)$ is fed to the next step to determine the optimum traffic density of the HOV/HOT lane.

3.1.3 Transportation Network Optimization

In this step, the total traffic density of segment i at time step $(t+T)$ is fed into the objective function. The optimum traffic density of the HOV/HOT lane is then determined for which total passengers travel time will be minimized. As discussed previously, minimizing the objective function is done every 60 seconds. This means that at the beginning of each time interval, the optimum HOV/HOT lane traffic density is predicted for the future 60 seconds by minimizing the total travel time that is experienced by total passengers driving in segment i during these 60 seconds.

Newell's triangular traffic model is adopted to explain the relationship between flow, density, and traffic speed in the objective function (Fig. 3.3).

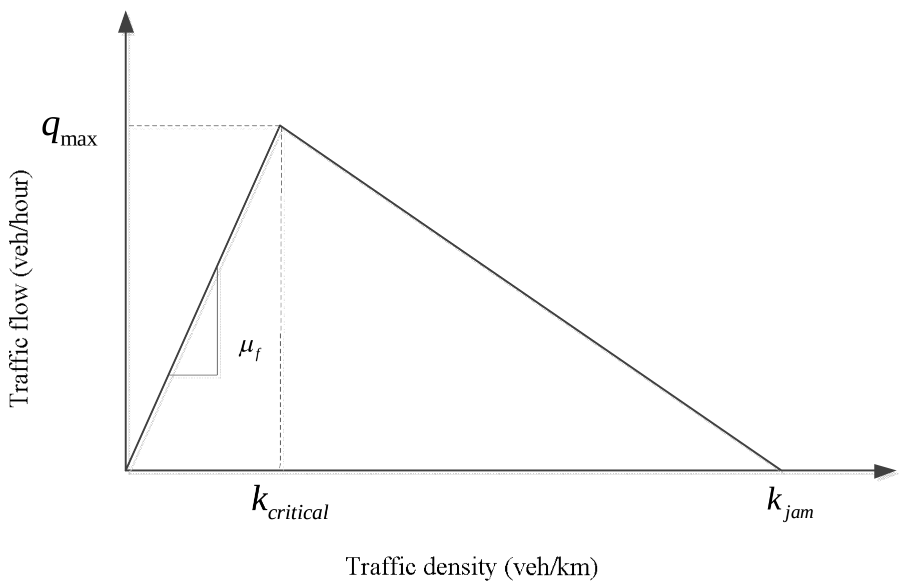

Figure 3. 3. Newell triangular traffic model (source: Newell, 1993)

Newell’s traffic model is a two-phase traffic model which consists of uncongested and congested traffic phases. For the traffic density between zero and the critical density ($k_{critical}$), the traffic state is uncongested and the traffic speed is free flow speed (μ_f); whereas, for traffic density values greater than the critical density, the traffic state will be congested. The maximum traffic density on a certain link cannot go beyond the jam density (k_{jam}). In this model, the maximum traffic flow (q_{max}) corresponds to the critical density. All of these parameters are the characteristics of a road and are only dependent on the shape and geometry of a road.

Traffic speed of segment i at time step t can be expressed below based on Newell's traffic model:

$$\mu_i(t+T) = \begin{cases} \mu_f & k_i(t+T) < k_c \\ \dfrac{\mu_f}{\left(\dfrac{k_j}{k_c} - 1\right)} \left(\dfrac{k_j}{k_i(t+T)} - 1\right) & k_c \leq k_i(t+T) \leq k_j \end{cases} \tag{3. 3}$$

Where:

$\mu_i(t+T)$ - Traffic speed of segment i at time step $(t+T)$ (km/hour)

μ_f - Free flow speed of segment i (km/hour)

k_j - Jam density of section i (vehicle/km)

k_c - Critical density of section i (vehicle/km)

In equation (3. 3), traffic flow speed of segment i at time step $(t+T)$ is free flow speed for the traffic density for uncongested traffic. By increasing the traffic density of segment i, the traffic speed will be decreased in the congested state of traffic.

Segment travel time using Newell's traffic model can be calculated based on equation (3. 4) as follows:

$$TT_i(t+T) = \begin{cases} \dfrac{L_i}{\mu_f} & k_i(t+T) < k_c \\ \dfrac{L_i\left(\dfrac{k_j}{k_c} - 1\right)}{\mu_f\left(\dfrac{k_j}{k_i(t+T)} - 1\right)} & k_c \leq k_i(t+T) \leq k_j \end{cases} \tag{3. 4}$$

Where:

$TT_i(t+T)$ - Travel time of segment i at time step $(t+T)$ (hour)

L_i - Length of segment i (km)

In equation (3. 4), the first part is the travel time for uncongested, and the second part is for congested traffic state.

Considering the travel time from equation (3. 4), total vehicular travel-time which is experienced at segment i at time step $(t+T)$ can be calculated by multiplying the travel time by

$L_i k_i(t+T)$, which is the total number of vehicles in segment i at time step $(t+T)$. Total vehicles travel-time by segment is expressed in equation (3. 5):

$$TVT_i(t+T) = \begin{cases} \dfrac{L_i^{\,2} k_i(t+T)}{\mu_f} & k_i(t+T) < k_c \\ \dfrac{L_i^{\,2} k_i(t+T)\left(\dfrac{k_j}{k_c} - 1\right)}{\mu_f\left(\dfrac{k_j}{k_i(t+T)} - 1\right)} & k_c \leq k_i(t+T) \leq k_j \end{cases} \quad (3.\ 5)$$

Where:

$TVT_i(t+T)$ - Total vehicles travel-time of segment i at time step $(t+T)$ (hour)

Since the objective of this study is to maximize the impact of HOV/HOT lanes in reducing total congestion costs, the following objective function is developed:

$$TPT(t+T) = \sum_{j=1}^{m} TPT_j(t+T) \quad (3.\ 6)$$

Where:

$TPT(t+T)$ - Total passengers' travel-time of segment i at time step $(t+T)$ (hour)

$TPT_j(t+T)$ - Total passengers' travel-time of lane j of segment i (hour)

m - Number of lanes of segment i

Depending on the magnitude of the predicted value for total traffic density of segment i at time step $(t+T)$, different lane traffic scenarios can be anticipated for segment i, as shown in Table 3.1. To determine the optimum toll rate at each time step, after identifying the magnitude of the total traffic density, all possible combinations of traffic density in the HOV/HOT lane and general lanes should be examined to determine which of these scenarios result in minimum total passenger travel-time. First of all, the traffic states associated with total density should be determined using Table 3.1. Then, total passenger travel-time of all possible traffic states associated with that specific density should be calculated, and the smallest one should be considered as the optimum passenger travel-time. The HOV/HOT lane density corresponding to the optimum traffic state should be considered final, and the toll rate will be determined based on the HOV/HOT share of the total density.

Table 3.1. Possible traffic states corresponding to different traffic density values

Traffic Density Classes	Traffic State			
	All lanes uncongested	Only HOV/HOT congested	All GP lanes congested, HOV/HOT lane not congested	All lanes congested
$0 \leq k_i(t + T) \leq k_c$	✓			
$k_c < k_i(t + T) \leq (m - 1)k_c$	✓	✓		
$(m - 1)k_c < k_i(t + T) \leq mk_c$	✓	✓	✓	
$mk_c < k_i(t + T) \leq (m-1)k_c + k_j$		✓	✓	✓
$(m - 1)k_c + k_j < k_i(t + T) \leq (m - 1)k_j + k_c$			✓	✓
$(m - 1)k_j + k_c < k_i(t + T) \leq mk_j$				✓

Table 3.1 explains all possible traffic conditions that can be seen on segment i with m lanes. For example, in the first row, if total vehicle density observed on segment i at at time step $(t + T)$ is less than the critical density, then all segment i lanes will be uncongested. In order to explain a more complex situation, consider the fourth row, in which the total observed density of segment i at at time step $(t + T)$ before HOV/HOT lane implementation is between mk_c and $(m-1)k_c + k_j$.

In this case, three different traffic states may occur in the case that the HOV/HOT lane is implemented:

- Only HOV/HOT is congested:

Depending on the value of the total observed density ranging from mk_c and $(m-1)k_c + k_j$, the total density of the HOV/HOT lane can be adjusted from ($k_c + 1$) to k_j, and the remaining density will be distributed evenly among the GP lanes to keep the density level of GP lanes at the critical density. This means that in this state, traffic density in the GP lanes is always critical density. If the total traffic density at the maximum density level -$(m-1)k_c + k_j$-, increases, this extra increase should be distributed between GP lanes since there is no more capacity in the HOV/HOT lane. Consequently, there is no longer an uncongested situation in the GP lane.

- All GP lanes are congested, and HOV/HOT is not congested:

Again, depending on the value of the total density ranging from mk_c and $(m-1)k_c + k_j$, the total density of the HOV/HOT lane can be adjusted from ($k_c + 1$) to k_j, and the remaining density will be distributed evenly between the GP lanes. In this case, density in each GP lane ranges from $(\frac{m}{m-1})k_c$ to $k_c + (\frac{k_j}{m-1})$, if HOV/HOT density is set as zero, and it ranges from k_c and $k_c + (\frac{k_j-k_c}{m-1})$, if HOV/HOT lane density is set as k_c. So, for the two extreme values, the GP lanes are congested.

- All lanes are congested:

Depending on the value of the total density ranging from mk_c and $(m-1)k_c + k_j$, the density can be distributed between the HOV/HOT and GP lanes such that all lanes become congested. For example, assuming the minimum possible amount in the interval - $mk_c + \epsilon$- if the traffic density is distributed evenly between all lanes, the density of each lane will be $\frac{mk_c+\epsilon}{m} = k_c + \epsilon$, which means that all lanes, including HOV/HOT and the GP lanes, are congested.

Depending on the possible traffic states, the objective function expressed in equation (3. 6) can be rewritten as four different equations as follows:

If all lanes are considered uncongested, then total passenger travel-time is:

$$TPT(t+T) = \sum_{r=2}^{p} \frac{r a_r L_i^2 k_H(t+T)}{\mu_f} + \left[k_H(t+T) - \sum_{r=2}^{p} a_r k_i(t+T)\right]\left(\frac{L_i^2}{\mu_f}\right) + \frac{(m-1) L_i^2 k_G(t+T)}{\mu_f} \qquad (3.\ 7)$$

The objective function is subject to:

$$k_H(t+T) + (m-1)k_G(t+T) = k_i(t+T) \qquad (3.\ 8)$$

$$0 \le k_H(t+T) \le k_c \qquad (3.\ 9)$$

$$0 \le k_G(t+T) \le k_c \qquad (3.\ 10)$$

Where:

$r = (2,3,4,\dots,p)$ – Auto occupancy of high occupancy vehicles

$a_r = (a_2, a_3, a_4, \dots, a_p)$ – Proportion of high occupancy vehicles

$k_H(t+T)$ – HOV/HOT lane traffic density of section i at time step $(t+T)$ (vehicle/km)

$k_G(t+T)$ - GP lanes traffic density of section i at time step $(t+T)$ (vehicle/km)

The objective function shown in equation (3. 7) consists of three objectives as follows:

– $\sum_{r=2}^{p} \frac{r a_r L_i^2 k_H(t+T)}{\mu_f}$ shows the total travel-time which is experienced by passengers in high occupancy vehicles taking the HOV/HOT lane.

– $\left[k_H(t+T) - \sum_{r=2}^{p} a_r k_i(t+T)\right]\left(\frac{L_i^2}{\mu_f}\right)$ represents the total travel-time of the passengers in the single occupancy vehicles who pay the toll to take the HOV/HOT lane and, finally,

– $\frac{(m-1)L_i^2 k_G(t+T)}{\mu_f}$ is the total travel-time of the passengers in single occupancy vehicles commuting in the general lanes.

The first constraint shown as equation (3. 8) ensures that the total number of vehicles travelling in the HOV/HOT and GP lanes is equal to the total number of vehicles travelling on segment **i** at time step $(t + T)$. The constraints in equations (3. 9) and (3. 10) ensure that the HOV/HOT lane and GP lanes are uncongested, respectively.

If only the HOV/HOT lane is congested:

$$\begin{aligned} TPT(t+T) = {} & \sum_{r=2}^{p} ra_r k_i(t+T)\left[\frac{L_i^2 k_H(t+T)(k_j-k_c)}{k_c\mu_f\left[k_j-k_H(t+T)\right]}\right] \\ & + \left[k_H(t+T) - \sum_{r=2}^{p} a_r k_i(t+T)\right]\left[\frac{L_i^2 k_H(t+T)(k_j-k_c)}{k_c\mu_f\left[k_j-k_H(t+T)\right]}\right] \\ & + \frac{(m-1)L_i^2 k_G(t+T)}{\mu_f} \end{aligned} \qquad (3.\ 11)$$

The objective function is subject to:

$$k_H(t+T) + (m-1)k_G(t+T) = k_i(t+T) \qquad (3.\ 12)$$

$$k_c < k_H(t+T) \leq k_j \qquad (3.\ 13)$$

$$0 \leq k_G(t+T) \leq k_c \qquad (3.\ 14)$$

Similar to the objective function shown in equation (3. 7), the objective function represented as equation (3. 11) includes three objectives:

– $\sum_{r=2}^{p} ra_r k_i(t+T)\left[\frac{L_i^2 k_H(t+T)(k_j-k_c)}{k_c\,\mu_f\left[k_j-k_H(t+T)\right]}\right]$ minimizes the total passengers travel-time of high occupancy vehicles traveling in the HOV/HOT lane.

– $\left[k_H(t+T) - \sum_{r=2}^{p} a_r k_i(t+T)\right]\left[\frac{L_i^2 k_H(t+T)(k_j-k_c)}{k_c\mu_f[k_j-k_H(t+T)]}\right]$ minimizes the total passengers travel-time of single occupancy vehicles traveling in the HOV/HOT lane and

– $\frac{(m-1)L_i^2 k_G(t+T)}{\mu_f}$ minimizes the total passengers travel-time of the single occupancy vehicles in the general lanes.

The constraint shown as equation (3. 12) is exactly the same as the constraint (3. 8). The constraints in equations (3. 13) and (3. 14) ensure that the HOV/HOT lane and GP lanes are congested and uncongested, respectively.

If all GP lanes are congested, and the HOV/HOT lane is not congested:

$$TPT(t+T) = \sum_{r=2}^{p} \frac{r a_r L_i^2 k_H(t+T)}{\mu_f} + \left[k_H(t+T) - \sum_{r=2}^{p} a_r k_i(t+T)\right]\left(\frac{L_i^2}{\mu_f}\right) + (m-1)\left[\frac{L_i^2 k_G(t+T)^2 (k_j-k_c)}{k_c\mu_f[k_j-k_G(t+T)]}\right] \tag{3. 15}$$

The objective function is subject to:

$$k_H(t+T) + (m-1)k_G(t+T) = k_i(t+T) \tag{3. 16}$$

$$0 \le k_H(t+T) \le k_c \tag{3. 17}$$

$$k_c < k_G(t+T) \le k_j \tag{3. 18}$$

The first and the second objectives of equation (3. 15) are the same as the first and the second parts of equation (3. 7) and represent the total passengers of high occupancy vehicles taking the HOV/HOT lane and the total travel-time of the passengers in single occupancy vehicles who pay the toll to take the HOV/HOT lane, respectively. The third objective - $(m-\left[\frac{L_i^2 k_G(t+T)^2(k_j-k_c)}{k_c\mu_f[k_j-k_G(t+T)]}\right])$ - is the total travel-time of the passengers in single occupancy vehicles travelling in the general lanes.

Again, constraint (3. 16) is the same as equations (3. 8) and (3. 12). The constraints (3. 17) and (3. 18) ensure that the HOV/HOT lane and GP lanes are uncongested and congested, respectively.

If all lanes, including HOV/HOT lane and GP lanes, are congested:

$$\begin{aligned}\mathrm{TPT}(t+T) = {} & \sum_{r=2}^{p} r a_r k_i(t+T)\left[\frac{L_i^2 k_H(t+T)(k_j-k_c)}{k_c \mu_f [k_j - k_H(t+T)]}\right] \\ & + \left[k_H(t+T) - \sum_{r=2}^{p} a_r k_i(t+T)\right]\left[\frac{L_i^2 k_H(t+T)(k_j-k_c)}{k_c \mu_f [k_j - k_H(t+T)]}\right] \\ & + (m-1)\left[\frac{L_i^2 k_G(t+T)^2(k_j-k_c)}{k_c \mu_f [k_j - k_G(t+T)]}\right]\end{aligned} \qquad (3.\ 19)$$

The objective function is subject to:

$$k_H(t+T) + (m-1)k_G(t+T) = k_i(t+T) \qquad (3.\ 20)$$

$$k_c \le k_H(t+T) \le k_j \qquad (3.\ 21)$$

$$k_c < k_G(t+T) \le k_j \qquad (3.\ 22)$$

Again, the objective function represented as equation (3. 19) includes three objectives:

- $\sum_{r=2}^{p} r a_r k_i(t+T)\left[\frac{L_i^2 k_H(t+T)(k_j-k_c)}{k_c \mu_f [k_j - k_H(t+T)]}\right]$ demonstrates the total passenger travel-time of high occupancy vehicles taking the HOV/HOT lane.
- $\left[k_H(t+T) - \sum_{r=2}^{p} a_r k_i(t+T)\right]\left[\frac{L_i^2 k_H(t+T)(k_j-k_c)}{k_c \mu_f [k_j - k_H(t+T)]}\right]$ represents the total travel-time of passengers in single occupancy vehicles who take the HOV/HOT lane and
- $(m-1)\left[\frac{L_i^2 k_G(t+T)^2(k_j-k_c)}{k_c \mu_f [k_j - k_G(t+T)]}\right]$ - is the total passenger travel-time of single occupancy vehicles travelling in the general lanes.

The first constraint is again repeated in this minimization problem. The constraints in equations (3. 21) and (3. 22) ensure that the HOV/HOT lane and GP lanes are congested.

In the system-wide optimization step, after identifying the appropriate class for the predicted value of the traffic density of segment i at time step $(t + T)$ –the traffic density before HOV/HOT implementation- all possible objective functions corresponding to all possible traffic states –after HOV/HOT deployment- should be solved and minimized, then the optimum $TPT(t + T)$ should be compared. The $k_H(t + T)$ that corresponds to the minimum $TPT(t + T)$ among all possible total passenger travel-time values determines the optimum HOV/HOT lane traffic density at time step $(t + T)$ - $k_H(t + T)$ - that should be fed to the next step to determine the optimum toll rate which needs to be implemented in the HOV/HOT lane to charge single occupancy vehicles taking the HOV/HOT lane.

3.1.4 Optimum Toll Rate Determination and Implementation

A simulation toll pricing model known as TPM (Sinprasertkool et al., 2011), is utilized in this study to split the total density of segment i at time step $(t + T)$ between the HOV/HOT lane and the general purpose lanes. Since travelling on general purpose (GP) lanes is free of charge for single occupancy vehicles, based on Wardrop's first principle, (Wardrop, 1952) the traffic volume entering the general lanes is split between these lanes such that the travel time of taking each GP lane becomes equal. The model predicts the density split between GP lanes and HOV/HOT lane based on price elasticity and the percentage of passengers who are willing to pay a toll to use the HOV/HOT lane. This methodology has extended the concept of the first Wardrop principle to user equilibrium in the context of GP lanes versus HOV/HOT lane.

Wardrop’s first principle states that all feasible routes between each pair of origin-destination nodes in a transportation network have the same travel cost under the user equilibrium condition. So, if the only cost applied to the parallel routes is the time spent driving, then the travel time of the routes is equal under user equilibrium condition. However, in the context of a network with both HOV/HOT lane and GP lanes as parallel routes, Wardrop's first principal cannot be applied directly since the travel time in the HOV/HOT lane is expected to be significantly lower than the travel time in the GP lanes.

In this context, user equilibrium is achieved when the cost of time saving enhanced by taking the HOV/HOT lane is equal to the toll rate. The new user equilibrium condition can be stated as follows in equation (3. 23):

$$(\mathrm{VOT})\mathrm{TT}_{\mathrm{HOT}} + \mathrm{TR}(t) = (\mathrm{VOT})\mathrm{TT}_{\mathrm{GL}} \tag{3. 23}$$

Where:

VOT – Value of time ($)

$\mathrm{TT}_{\mathrm{HOT}}$ – Travel time of taking HOV/HOT lane (hour)

$\mathrm{TT}_{\mathrm{GL}}$ – Travel time of taking general purpose lane (hour)

$\mathrm{TR}(t)$ – Toll rate at time step t ($)

VOT is the amount that the users are willing to pay to save one unit of time, which is considered to be one hour. In general, the appropriate amount for VOT value can be obtained by a number of approaches, such as survey data, focus group studies, and observed preference data to estimate the value of time (Olyai and Ardekani, 2013).

Equation (3. 23) can be rewritten as equation (3. 24):

$$\mathrm{TR}(t) = \mathrm{VOT}(\mathrm{TT}_{\mathrm{GL}} - \mathrm{TT}_{\mathrm{HOT}}) \tag{3. 24}$$

Based on Newell's triangular traffic model, depending on the optimum $k_{H}(t + T)$ -which determines whether or not GP lanes and HOV/HOT lane are congested - four different equations emerge from equation (3. 24) as follows:

If all lanes are uncongested:

$$TR(t + T) = VOT\left[\frac{L_i}{\mu_f} - \frac{L_i}{\mu_f}\right] = 0 \tag{3. 25}$$

If only the HOV/HOT lane is congested:

$$TR(t + T) = VOT[\frac{L_i}{\mu_f} - \frac{L_i\left(\frac{k_j}{k_c} - 1\right)}{\mu_f\left(\frac{k_j}{k_H(t + T)} - 1\right)}] \tag{3. 26}$$

If general lanes are congested:

$$TR(t + T) = VOT[\frac{L_i\left(\frac{k_j}{k_c} - 1\right)}{\mu_f\left(\frac{k_j}{k_G(t + T)} - 1\right)} - \frac{L_i}{\mu_f}] \tag{3. 27}$$

If all lanes are congested:

$$TR(t + T) = VOT[\frac{L_i\left(\frac{k_j}{k_c} - 1\right)}{\mu_f\left(\frac{k_j}{k_G(t + T)} - 1\right)} - \frac{L_i\left(\frac{k_j}{k_c} - 1\right)}{\mu_f\left(\frac{k_j}{k_H(t + T)} - 1\right)}] \tag{3. 28}$$

As can be seen in equation (3. 25), during off-peak traffic hours, the toll rate should be zero. In other words, the shoulder should be closed in this case since this additional lane is not needed.

Finally, the toll rate value corresponding to the earlier time step $t + T$ is considered final and implemented.

3.2 Case Study and Results

In this section, the proposed HOV/HOT lane algorithm is tested on the case study network using QUADSTONE PARAMICS, which is a powerful traffic microsimulation software. The HOV/HOT lane algorithm is tested on the simulated real world transportation network in Calgary, Alberta. The section is part of a highway with several on-ramps and off-ramps.

The network has been run 10 times for each traffic scenario using PARAMICS Modeler. Each run corresponds to different seeds, and the following data have been aggregated using PARAMICS Analyzer:

- Motorway travel-time (second/vehicle)
- Motorway link delay (second/vehicle)
- Motorway count data (vehicle/hour)
- Motorway density (vehicle/kilometer)
- Total network travel-time (second/vehicle)
- Total network link delay (second/vehicle)
- Total network count data (vehicle/hour)

As mentioned in Chapter One, total delayed time cost and wasted fuel under traffic congestion are the major contributors to total Calgary congestion cost by around 90% and 7%, respectively. Thus to determine the initial impact of implementing HOV/HOT lanes on total Calgary congestion costs, the potential impact of deploying HOV/HOT lanes on total delayed time and total wasted fuel consumption needs to be calculated. Total network link delay and total vehicular network count obtained by PARAMICS Analyzer are useful data to estimate the magnitude of the HOV/HOT lane implementation impact on total network delay time.

The other two measures of driving total congestion cost, such as the total wasted fuel consumption cost and monetized environmental impact, can be assessed by using PARAMICS Monitor. PARAMICS Monitor is an emission simulator plugin which is able to estimate the emission from the tailpipe of motor vehicles, including NO_x, CO_2, CO, PM, and CH_4 emissions.

Having the ability to estimate the potential impact of implementing HOV/HOT lanes on total transportation network delay time, total wasted fuel volume and total network GHG emissions, QUADSTONE PARAMICS is an effective tool to estimate the initial impact –alternatively called the operating phase- of deploying the HOV/HOT temporary shoulder use model.

3.2.1 Case Study Network Description

Deerfoot Trail is the major north-south transportation freeway through the City of Calgary and is a section of Queen Elizabeth II Highway -also known as Highway 2- in Calgary, Alberta, Canada. Deerfoot Trail stretches 50 km from the City of Calgary's northern limit to its merger with Macleod Trail in the south. The annual daily traffic volume ranges between 27,000 and 158,000 vehicles (including cars and trucks), with an average annual daily traffic (AADT) of 170,000 vehicles in 2008 (The City of Calgary, 2010).

For the aim of this study, the 7.5 km section of Deerfoot Trail between McKnight Drive and Memorial Drive is selected. This section includes four on-ramps as well as four off-ramps, and stretches from northeast to southeast Calgary.

Fig. 3.4 shows the case study section of Deerfoot Trail taken from Google Maps. This section is then coded using QUADSTONE PARAMICS Modeler.

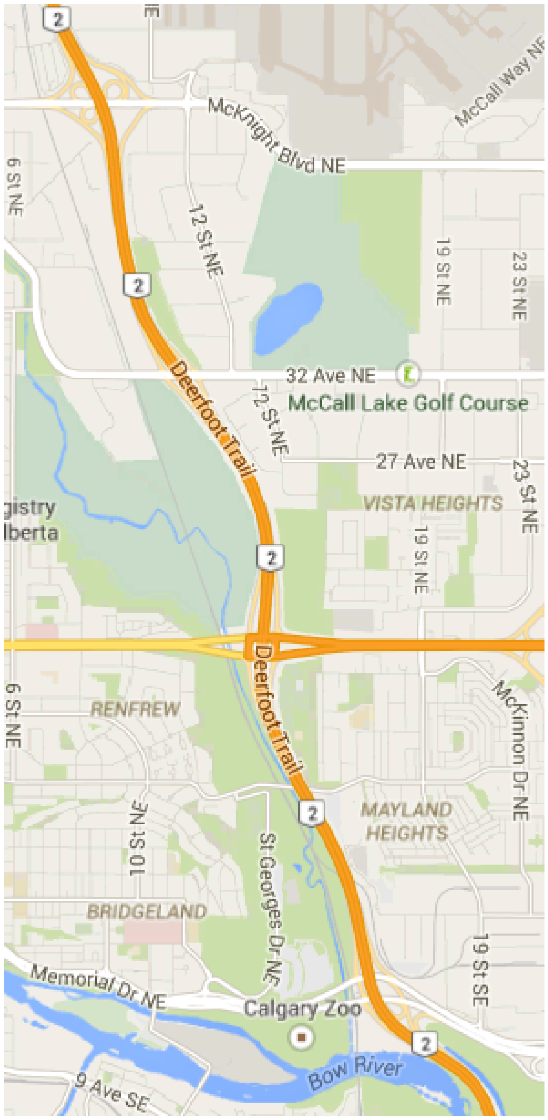

Figure 3. 4. The study area: Deerfoot Trail between McKnight and Memorial Drive (Google Maps)

The model parameters of the PARAMICS model (i.e., the mean headway factor and the mean reaction time) were previously calibrated by the transportation group at the University of Calgary. A 2006 seed origin-destination matrix provided by the City of Calgary was also calibrated using PARAMICS Modeler to reflect 2012 vehicle count provided on the Alberta Transportation website (www.transportation.alberta.ca/). The simulated traffic flow resulting by assigning the calibrated OD estimation method had an average Geoffrey E. Havers (GEH) statistic of 5.0. GEH statistics compare the measured counts to the simulated counts. The general formula for calculating GEH is shown as equation (3. 29).

$$GEH = \frac{1}{N}\sum_{n=1}^{N}\sqrt{\frac{2(X_n^s - X_n^o)^2}{X_n^s + X_n^o}} \qquad (3.\ 29)$$

Where:

N – Number of observations

X_n^o – Observed value at time n

X_n^s – Simulated value at time n

The majority stretch of this freeway section has four lanes. There are also some segments with three lanes and only one segment with five lanes. No managed lane –including HOV/HOT or high occupancy vehicle (HOV) lane- is currently deployed in the study area.

Currently, QUADSTONE PARAMICS offers one specific toolbox to model two types of HOV/HOT lane modelling:

1) Scheduled toll pricing
2) Dynamic toll pricing

In the scheduled toll pricing method, only three control variables including time interval during which certain amount of toll is implemented, toll rate and VOT value can be adjusted in order to implement HOV/HOT lanes in the study area. In the dynamic toll pricing method, the toll amount is changed to keep the traffic speed in the HOV/HOT lane at a certain level. Two variables can be adjusted to control this type of toll pricing: the desired traffic speed in the HOV/HOT lane and VOT.

Due to limited ability of PARAMICS toll pricing toolbox to model varied HOV/HOT implementation approaches, an application programming interface (API) was developed in order to implement the developed approach. The section of Deerfoot Trail considered in this study is divided into 11 different sections based on the location of on-ramps and off-ramps, and also the number of lanes of each section. The specifications of each motorway section are shown in Table 3.2.

Table 3.2. Specification of each road segment

Section number	Section length (km)	Number of lanes
1	0.76	3
2	0.58	4
3	0.84	4
4	0.17	5
5	0.48	4
6	0.58	4
7	0.70	3
8	1.16	4
9	1.19	3
10	0.33	4
11	0.73	3

The real time SMS data needed to calculate optimum toll rate at each time step are obtained from probe vehicles for each motorway section. The SMS of each section is then used as an input to the model to obtain the optimum traffic density of the HOV/HOT lane. In this study, the probe vehicles penetration rate is considered as 10% which is the same as the proportion of travel time data collected by Bluetooth devices implemented on Deerfoot Trail. This amount of penetration rate can be easily changed in PARAMICS API. Based on the proposed model, the API collects the SMS data at a frequency of three seconds. After determining the optimum toll rate, API updates the toll rate every 60 seconds.

For each traffic scenario, 10 different runs with different seed values were conducted. These seeds are random numbers which are utilized by PARAMICS to change the specification of each traffic scenario, including car following, lane changing, release of vehicles, route choice, etc. Each run took 1 hour and 15 minutes (AM peak for the southbound direction), during which the first 15 minutes was considered as the warm-up period. Thus, the output data of this warm-up period are disregarded in the analysis. The output data of the remaining 1 hour AM peak are then extracted from the study area using PARAMICS Analyzer for before and after HOV/HOT lane deployment to determine the initial impact of deploying HOV/HOT lanes on the total Calgary congestion costs.

3.2.2 Newell's Traffic Model of the Study Area

As mentioned previously, since the triangular Newell's traffic model represents more realistic attributes of real word traffic problems, this model is adopted to represent the traffic specification of the study area. These data accompanied with the specified values and the methods that they were obtained with are shown in Table 3.3. The schematic of this model is also shown in Fig. 3.5 (Arora et al., 2014).

Table 3. 3. Traffic parameters for Newell's triangular model for the study area

Parameter	Method used to estimate	Value
Capacity	Highway capacity manual (HCM, 2010)	2400 veh/h
Free flow speed	Least-squares fit	95 km/h
Critical density	Horizontal projection on the maximum flow	26 veh/km
Jam density	Plotting regression line for the congested side of the curve and allowing the line to pass through the tip of the flow-density diagram	122 veh/km

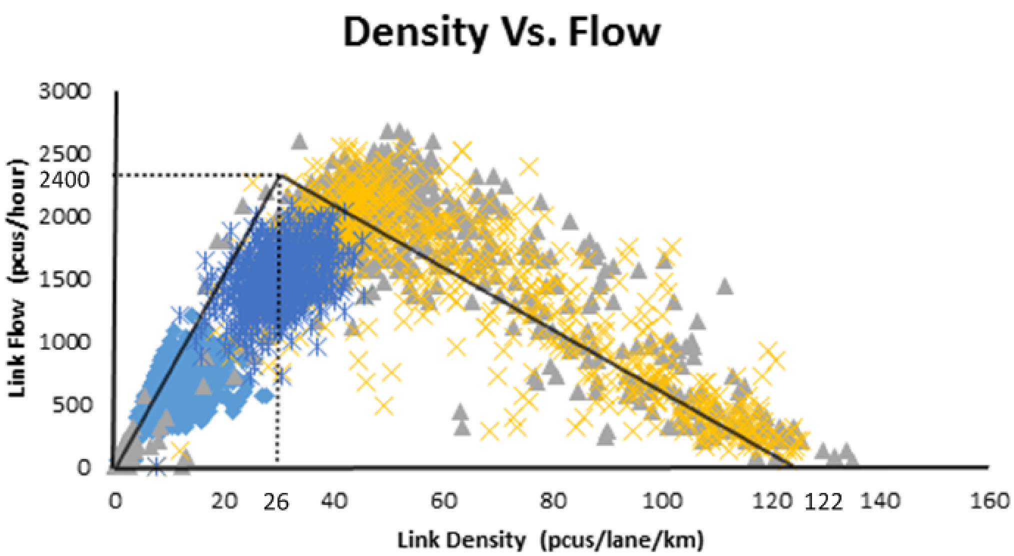

Figure 3. 5. Newell's traffic model for Deerfoot Trail (source: Arora et al., 2014)

Using the parameters of Table 3.2, equation (3.3) can be rewritten as equation (3.30) for the study area as follows:

$$\mu_i(t+T) = \begin{cases} 95 & k_i(t+T) < 26 \\ 25.73\left(\dfrac{122}{k_i(t+T)} - 1\right) & 26 \le k_i(t+T) \le 122 \end{cases} \qquad (3.\ 30)$$

Consequently, total travel-time $-TT_i(t+T)-$ and total vehicle travel-time $-TT_i(t+T)-$ can be recalculated as shown in equations (3. 31) and (3. 32), respectively:

$$TT_i(t+T) = \begin{cases} \dfrac{L_i}{95} & k_i(t+T) < 26 \\ \dfrac{3.7L_i}{95\left(\dfrac{122}{k_i(t+T)} - 1\right)} & 26 \le k_i(t+T) \le 122 \end{cases} \qquad (3.\ 31)$$

$$TVT_i(t+T) = \begin{cases} \dfrac{L_i{}^2 k_i(t+T)}{95} & k_i(t+T) < 26 \\ \dfrac{3.7L_i{}^2 k_i(t+T)}{95\left(\dfrac{122}{k_i(t+T)} - 1\right)} & 26 \le k_i(t+T) \le 122 \end{cases} \qquad (3.\ 32)$$

Based on the fact that the section of Deerfoot Trail chosen for this study has motorway segments with three, four and five lanes, all possible density classes and the corresponding traffic states are shown in Table 3.4. In every PARAMICS simulation run, after identifying total traffic density extracted from probe vehicles on each motorway section, the API will first search for the appropriate density class to find and minimize the corresponding objective functions.

Table 3. 4. Possible traffic states for different traffic density values and lanes

Section number of lanes	Traffic density classes	Traffic state			
		All lanes uncongested	Only HOV/HOT congested	All GP lanes congested	All lanes congested
4 lanes	$0 \leq k_i(t + T) \leq 26$	✓			
	$26 \leq k_i(t + T) \leq 78$	✓	✓		
	$78 \leq k_i(t + T) \leq 104$	✓	✓	✓	
	$104 \leq k_i(t + T) \leq 200$		✓	✓	✓
	$200 \leq k_i(t + T) \leq 392$			✓	✓
	$392 \leq k_i(t + T) \leq 488$				✓
5 lanes	$0 \leq k_i(t + T) \leq 26$	✓			
	$26 \leq k_i(t + T) \leq 104$	✓	✓		
	$104 \leq k_i(t + T) \leq 130$	✓	✓	✓	
	$130 \leq k_i(t + T) \leq 226$		✓	✓	✓
	$226 \leq k_i(t + T) \leq 514$			✓	✓
	$514 \leq k_i(t + T) \leq 610$				✓
6 lanes	$0 \leq k_i(t + T) \leq 26$	✓			
	$26 \leq k_i(t + T) \leq 130$	✓	✓		
	$130 \leq k_i(t + T) \leq 156$	✓	✓	✓	
	$156 \leq k_i(t + T) \leq 252$		✓	✓	✓
	$252 \leq k_i(t + T) \leq 636$			✓	✓
	$636 \leq k_i(t + T) \leq 732$				✓

After identifying the appropriate density classes, the proper objective function should be minimized to determine the optimum traffic density of the HOV/HOT lane.

Based on the Mobility Monitor (2012), the share of high occupancy vehicles (HOV) entering Deerfoot Trail oscillated in the interval of (15%, 25%) between 1999 to 2011. In 1999, the SOV rate for inbound AM peak hour vehicles into Deerfoot Trail was 76%, climbing to 83% in 2009, and dropping to 80% in 2011. Conversely, the HOV rate was 24% in 1999, dropping to 17% in 2009, and climbing to 20% in 2011. However, the share of high occupancy vehicles entering Deerfoot Trail is different. Based on the most recent information provided by the City of Calgary, the share of SOV and HOV during peak traffic hours were 90% and 10%, respectively, in 2011. These data are used in this study to obtain the objective functions for different traffic scenarios. Since the data do not break down to the level of occupancy per vehicle, the following scenario for HOV shares is considered as shown in Table 3.5:

Table 3. 5. Deerfoot vehicle occupancy during peak hours

Vehicle type	Vehicle occupancy	Share
SOV	1	90%
HOV	2	7%
	3	2%
	4	1%

Considering the auto occupancy data provided in Table 3.4, the objective functions of the study area can be rewritten based on the general formulas expressed in equations (3. 7) to (3. 22).

Two basic scenarios are considered to evaluate the performance of the deployed managed lane: the existing scenario without the HOV/HOT lane and the scenario with HOV/HOT lane implementation. It is worth noting that this study does not assume that the presence of HOV/HOT induces more commuters to carpool. Thus, same vehicle occupancy is adopted for both scenarios.

After identifying the minimization problem for each time step, a PARAMICS API is then developed to implement the real time dynamic toll to the study area which is updated each minute. Each of these scenarios corresponds to the average of 10 PARAMICS runs with different random seeds. These random seeds are utilized by PARAMICS to calculate different traffic assignment parameters, such as release of demand, route choice, lane changing, car following, etc. All examined runs are conducted for 1 hour and 15 minutes (AM peak for the southbound traffic). The first 15 minutes of each run is considered as the warm-up period and disregarded from further analysis. Thus, the remaining full one hour is considered as the simulation period to evaluate the performance of each scenario.

3.2.3 Results

To evaluate the impact of HOV/HOT lane deployment on the total Calgary GHG emissions, it is essential to determine both the operating and the secondary phase environmental impact of HOV/HOT lane implementation. This would necessitate determining the changes in GHG emitted from vehicle exhausts, total vehicle fuel consumption, and total travel-time savings due to the HOV/HOT lane implementation. Moreover, the impact of HOV/HOT lane deployment on traffic measures, such as traffic flow, speed, and travel time should be evaluated to determine whether or not HOV/HOT can improve the traffic performance of highways.

3.2.3.1 Impact on Traffic Performances

After simulating the Deerfoot Trail model in PARAMICS Modeler the traffic data, including traffic flow, traffic speed, and total travel-time in the HOV/HOT and GP lanes were extracted using PARAMICS Analyzer.

Average link speed is an important measure of effectiveness for the HOV/HOT lane. The speed in the HOV/HOT lane should be close to the free flow speed. Moreover, the traffic speed of the HOV/HOT lane should be substantially higher than the traffic speed in the GP lanes to encourage SOV to use the HOV/HOT lane by paying the toll. Fig. 3.6 shows the link speed of the HOT/HOV lane versus the speed of the GP lanes.

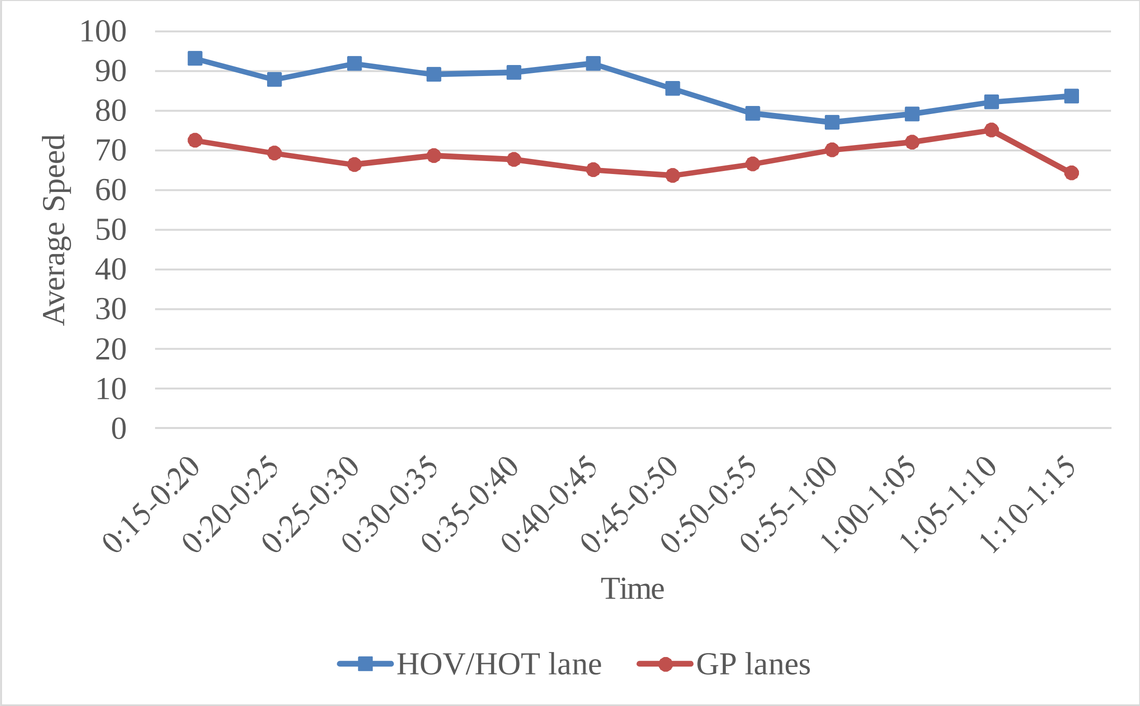

Figure 3. 6. Results of average speed by time interval for the HOV/HOT lane versus GP lanes

As can be seen in Fig. 3.7, traffic speed of the HOV/HOT lane is substantially higher than the link speed of the GP lanes. Moreover, HOV/HOT lane speed laid in the [80 km/h-95 km/h] interval for different time horizon which is very close to 95 km/h as the calibrated free flow speed of the Deerfoot Trail model. The speed differential between HOV/HOT lane and the GP lanes may arise some safety concerns. It is the case, especially near the access points to the HOV/Hot lane and the exit points to the GP lanes. These speed differential may cause small shockwave in the vicinity of these points which increases the chance of occurring accident. TO avoid this problem, many of the HOV/HOT lane in the real world are single entry-single exit.

Another important measure of the HOV/HOT lane performance is link travel-time. It is critical to know how much time will be saved using the HOV/HOT lane. On the other hand, the performance of the GP lanes before and after HOV/HOT implementation in terms of travel-time savings should be evaluated. Fig. 3.7 represents the link travel-time of the HOV/HOT lane and the GP lanes before and after HOV/HOT implementation.

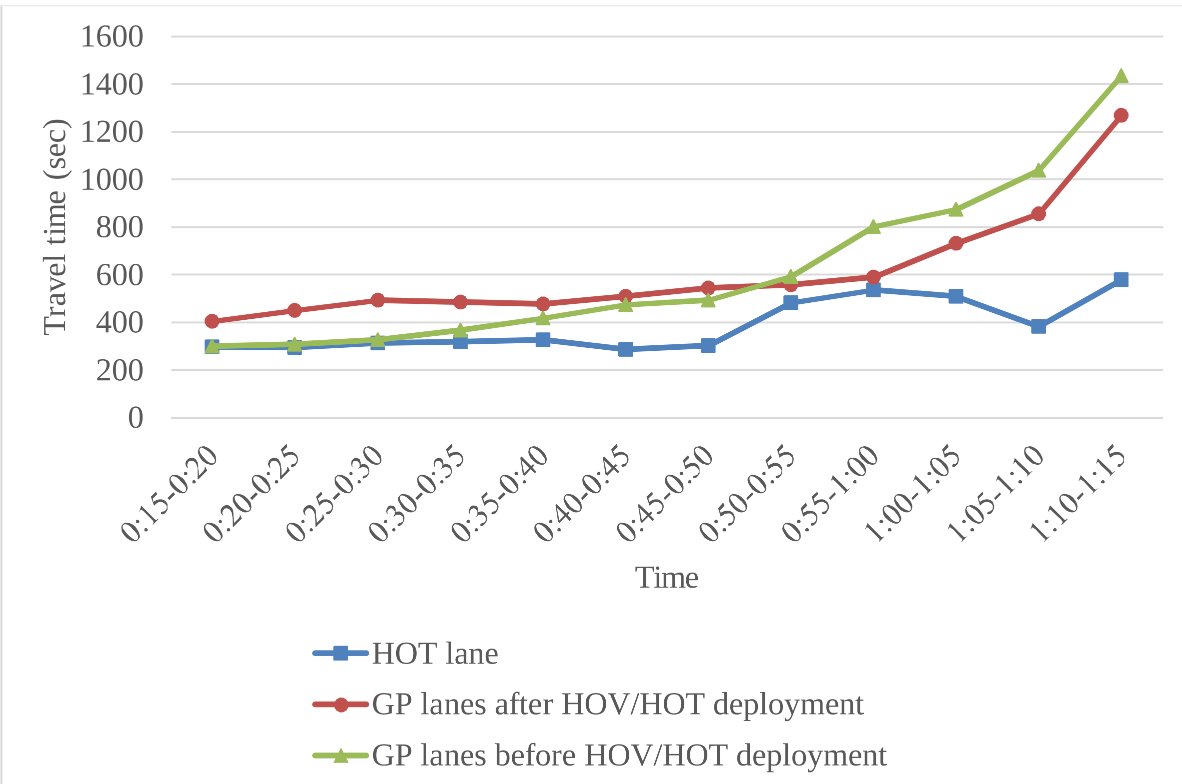

Figure 3. 7. Results of average travel time by time interval for the HOV/HOT lane versus GP lanes

As shown in Fig. 3.8, travel time of the HOV/HOT lane is lower than the travel time of the GP lanes, as can be expected from the higher traffic speed of the HOV/HOT lane after implementing the HOV/HOT lane, as shown in Fig. 3.7. Considering the GP lanes, two different situations were observed. In the [0:15-0:50] time interval, although the link travel-time of the GP lanes before HOV/HOT deployment is slightly higher than that of the GP lanes in the case of no toll charge, it is steady over time with only small oscillations. In the [0:50-1:15] time interval, where the transportation network is highly congested, the GP lanes in the present toll charge have substantially lower link travel-time.

Traffic throughput can be used as a measure of HOV/HOT utilization. Fig. 3.8 shows the throughput for the HOV/HOT lane, and total freeway throughput before and after HOV/HOT implementation.

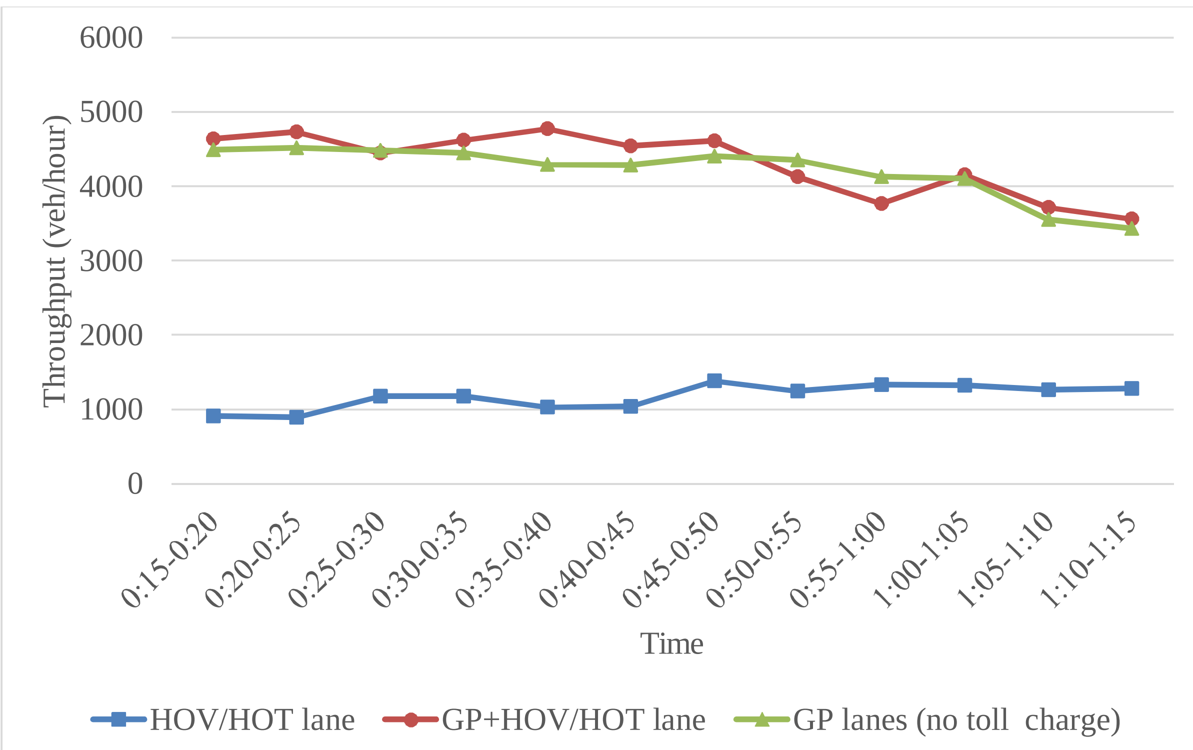

Figure 3. 8. Results of average throughput by time interval for the HOV/HOT lane versus GP lanes

Considering total freeway throughput, the current HOV/HOT model is able to generate steady traffic flow in the HOV/HOT lane with small oscillations. Most of the time, total traffic throughput of the tolled scenario is higher than the throughput in the case in which there is no toll charge. However, there are more oscillations in the traffic flow of the tolled scenario, especially during the [0:50-1:05] time interval when the network is congested. This can be considered as the effect of merging and diverging maneuvers near the access point to the HOV/HOT and the exit point to the GP lanes.

3.2.3.2 Impact on Emissions

Emissions analysis has been conducted by using data obtained from using the PARAMICS module PARAMICS Monitor. This software plugin collects pollution and emission levels for every link in the network by summing the emissions for each individual vehicle within the link. 16 different types of vehicles including cars, trucks and transit with various length can be modeled in PARAMICS. One of the limitations of this study is that it does not consider the proportion of hybrid cars and model year in estimating the emissions. PARAMICS Monitor determines the level of emissions by considering the vehicle type, speed, acceleration, time on the network, and link gradient. The modelled parameters are compared with predefined emission distributions to calculate the level of emissions for a specific time step.

PARAMICS Monitor provided emissions statistics regarding the following pollutants (units):

- Carbon Monoxide (mg)
- Carbon Dioxide (mg)
- Total Hydrocarbons (mg)
- Oxides of Nitrogen (mg)
- Particulate matter (µg)

Emission statistics collected from the case study are shown in Table 3.6 for both before and after HOV/HOT lane deployment scenarios.

Table 3. 6. Total estimated network emissions

Scenario	Carbon Monoxide (tonne/hour)	Carbon Dioxide (tonne/hour)	Total Hydrocarbons (tonne/hour)	Oxides of Nitrogen (tonne/hour)	Particulate matter (Kg/hour)
Without HOV/HOT lane	4.97	88.70	0.911	1.033	3.45
With HOV/HOT lane	4.93	87.22	0.913	0.998	3.39
Change	-1.66%	-0.86%	+0.22%	-3.44%	-1.84%

After implementing the HOV/HOT lane, the emissions of oxides of nitrogen, particulate matter, carbon dioxide and carbon monoxide were reduced by 3.44%, 1.84%, 1.66% and 0.86%, respectively. However, hydrocarbon emissions increased slightly by 0.22%. Hydrocarbons are basically raw fuels and are released to the atmosphere as a result of incomplete combustion of fossil fuels, or when fuel evaporates.

The greenhouse gas emissions include the emissions of water vapor, carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O), Sulfur hexafluoride (SF_6), per fluorocarbon (PFCs), Hydro fluorocarbon (HFCs) and chlorofluorocarbons (CFCs) (C2ES, 2007). Thus, to calculate total GHG emission savings of implementing HOV/HOT lanes, corresponding CO_2 emission savings shown in Table 3.6 have been taken into account. Moreover the emission of N_2O as a GHG gas emitted from vehicle exhaust should be considered as well. The emission of N_2O is not reported directly by PARAMICS Monitor. Assuming gasoline as the major fuel consumed by the motor vehicle in Deerfoot Trail and based on the emission factors of the CO_2 and N_2O of the gasoline as 8.78

(g/short ton) and 0.08 (g/short ton) respectively (EPA, 2014), total N_2O emission saving is calculated below:

$$N_2Os = CO_2s \times \frac{ef_{N_2O}}{ef_{CO_2}} = 1.4761 \times \frac{0.08}{8.78} = 0.0134 \qquad (3.\ 33)$$

Where:

CO_2s – Carbon dioxide emission savings (tonne/hour)

N_2Os – Nitrous oxides emissions savings (tonne/hour)

ef_{N_2O} – N2O emission factor (g/tonne)

ef_{CO_2} – CO2 emission factor (g/tonne)

$$N_2Os = 1.4761 \times \frac{0.08}{8.78} = 0.0134\ \text{tonne/hour}$$

The most recent Greenhouse Gas Protocol (2007) is considered to convert the current emission savings to CO_2 equivalent emissions. Based on this report, every gram of CO_2 and N_2Oemissions are equivalent to 1 gram and 298 grams of CO_2 eq., respectively.

Total annual GHG emission savings is calculated using equation (3. 34):

$$TGHGs = (CO_2s + N_2Os * 298) \times ph \times n \qquad (3.\ 34)$$

Where:

$TGHGs$– Total annual GHG emission savings (tonne CO_2 eq.)

ph – Peak hours (hour/day)

n – Number of working days in a year (day)

Considering peak hours and the number of working days as 2 and 250, respectively (Business day calculator, 2013), total annual GHG emission savings due to HOV/HOT lane implementation is calculated as below:

$$TGHGs = (1.4761 + 0.0134 * 298)(\text{tonne}\ CO_2\ \text{eq.}) \times 2 \times 250 = 2{,}742.1\ \text{tonnes}\ CO_2\ \text{eq.}$$

This amount of savings in GHG emissions can be monetized by multiplying it by social cost of carbon (SCC). SCC is an estimate of the monetized damages associated with an incremental increase in carbon emissions in a given year. It is intended to include (but is not limited to) changes in net agricultural productivity, human health, property damages from increased flood risk, and the value of ecosystem services (United States Government, 2010). Based on the technical support document published by U.S. government (EPA, 2010), the social cost of CO_2 for 2015 is predicted as \$37.7 per each metric tonne CO_2 emission in the U.S. In the case of Canada, Environment Canada uses $\$25/\text{tonne } CO_2 \text{ eq.}$ (Sustainable Prosperity, 2011), and this value was used as the government guideline in this study to monetize the annual GHG emission savings. Different values can also be examined as part of a sensitivity analysis. The SCC is supposed to be comprehensive in terms of estimating the negative impact of CO_2 emission on human health, agricultural productivity and increasing flood risk, however, from academic point of view it is likely that SCC underestimates the damages, since it do not include all of the important physical, ecological and economic impacts of climate change (EPA, 2013). Total GHG emission cost-savings enhanced by HOV/HOT lane implementation can be calculated as follows:

$$\text{GHG emission cost savings} = 2{,}742.1\ (\text{tonne } CO_2 \text{ eq.}) \times 25 \left(\frac{\$}{\text{tonne } CO_2 \text{ eq.}}\right) = \$68{,}551.2$$

3.2.3.3 Impact on Fuel Consumption

PARAMICS Monitor was used to calculate the total network fuel consumption. By summing the total fuel consumption for all vehicles on a link, it produced a detailed report to include vehicle fuel consumption on each network link.

Total network fuel consumption is shown in Table 3.7 for both before and after HOV/HOT lane implementation scenarios. Fig. 3.9 also provides graphical comparison for before and after HOV/HOT lane deployment.

Table 3. 7. Total estimated network fuel consumption

Scenario	Fuel consumption (L/hour)
Without HOV/HOT lane	41,445.5
With HOV/HOT lane	40,755.5
Change	-1.66%

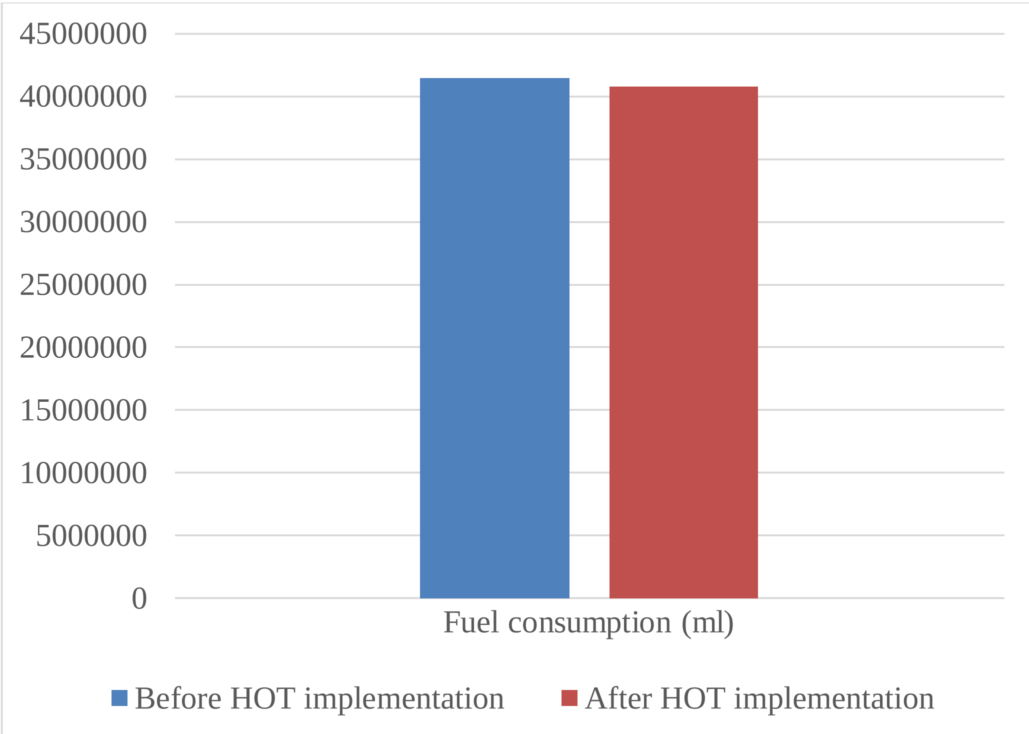

Figure 3. 9. Total network fuel consumption

Total annual fuel consumption savings was then calculated using equation (3. 35):

$$TFs = Fs \times ph \times n \qquad (3.\ 35)$$

Where:

TFs– Total annual network fuel savings (L)

Fs – Average network fuel savings during simulation period (L/hour)

Total annual network fuel savings is calculated as follows:

$$TFs = 689.96\ (L) \times 2 \times 250 = 344{,}978.9\ L$$

Considering \$1.19 as the average retail price for regular unleaded gasoline in Calgary (Statistics Canada, 2014), the monetized value corresponding to the total fuel savings will be:

$$\text{Total fuel cost savings} = 344978.9\ (\text{L}) \times 1.19\left(\frac{\$}{\text{L}}\right) = \$410{,}486.7$$

3.2.3.4 Impact on Travel Time

As discussed in the introduction, total delayed time is the major contributor to the total Calgary congestion costs, with a 90% share. This fact necessitates evaluating the HOV/HOT lane deployment impact on the total network travel-time to determine the potential savings of total congestion costs. Potential savings in total delayed time of the network can be determined by comparing the total passenger travel-time for before and after HOV/HOT lane deployment. Total link counts and link travel-time obtained from PARAMICS Analyzer are two measures that were used to estimate total passengers travel-time in the network.

Table 3.8 shows the average total vehicle travel-time savings in the study corridor (Deerfoot Trail) enhanced by HOV/HOT lane. The minimum and maximum savings associated with corresponding runs are also represented:

Table 3. 8. Total vehicle travel-time savings of Deerfoot Trail

Magnitude	Total vehicle travel-time savings (%)
Minimum	22.2
Maximum	38.7
Average	29.8

As can be seen in Table 3.8, HOV/HOT implementation will reduce total vehicle travel-time on the Deerfoot Trail by 29.8%, which is a significant savings in terms of reducing delay. Same level of travel time saving were reported in the similar studies on the same size transportation corridors. Jang et al. (2014) showed that implementing HOV/HOT lane on Gyungbu expressway in South Korea will decrease total vehicle travel time by 22%. In another study, Gardner et al. (2013) reported 33% reduction in average vehicle travel time.

Table 3.9 shows the total vehicle travel-time in the network for with and without HOV/HOT scenarios:

Table 3. 9. Total vehicle travel-time of the network

Scenario	Total vehicle travel-time (hour)
Without HOV/HOT lane	13,090
With HOV/HOT lane	12,869
Change	-1.7%

Based on the information provided by Table 3.9, implementing HOV/HOT lanes will decrease total vehicle travel-time by 1.70%. This is a significant improvement comparing to the similar studies conducted on the transportation networks with the same size. For example in the study conducted by Xiong et al. (2014) on implementing a new tolled freeway in the Baltimore region, total vehicle travel time saving during early and AM peak was reported as 0.39 %.

Using the vehicle occupancy information shown in Table 3.4, total passenger travel-time of the case study transportation network can be calculated using equation (3. 36):

$$\mathrm{TPT} = \sum_{r=1}^{p} r a_r \times \mathrm{TVT} \qquad (3.\ 36)$$

Where:

TPT– Total passenger travel-time (hour)

TVT – Total vehicle travel-time (hour)

$r = (1,2,3,4,\ldots,p)$ – Auto occupancy

$a_r = (a_1, a_2, a_3, a_4, \ldots, a_p)$ – Proportion of single and high occupancy vehicles

Total passengers travel-time of the network is shown in Table 3.10:

Table 3. 10. Total passengers travel-time of the network

Scenario	Total passengers travel-time (hour)
Without HOV/HOT lane	14,922
With HOV/HOT lane	14,671
Change	-1.7%

As a result, total passenger travel-time savings enhanced by HOV/HOT lane deployment is 251.79 hours (i.e., around 1.70%) during one hour simulation run of the total network. Total annual passenger travel-time cost-savings was then calculated using equation (3. 37):

$$\mathrm{ADTs} = \mathrm{TPTs} \times \mathrm{ph} \times \mathrm{n} \times \mathrm{VOT} \qquad (3.\ 37)$$

Where:

ATPTs– Annual delayed time cost-savings ($)

TPTs– Total passenger travel-time savings during simulation period (hour)

Considering the current value of time for the province of Alberta as $28.15 (Statistic Canada, 2014) and using equation (3. 35), total Calgary annual delay time cost-savings is calculated as follows:

$$\mathrm{ADTs} = 251.79(\mathrm{hour}) \times 2 \times 250 \times 28.15\left(\frac{\$}{\mathrm{hour}}\right) = \$3{,}543{,}948$$

3.2.3.5 Impact on Total Calgary Congestion Costs

As discussed in the introduction, total congestion cost consists of monetized value of GHG emission, total fuel consumption cost, and total delayed time cost-savings. Thus, total Calgary congestion cost-savings was calculated by adding up the corresponding values calculated in sections 3.2.3.1 through 3.2.3.3:

Table 3. 11. Total Calgary congestion cost-savings

	Monetized value ($)
GHG emission social cost-savings	68,551.2
Total fuel cost-savings	410,486.7
Total delayed time savings	3,543,948
Total congestion cost-savings	**4,022,986**

Compared to the total Calgary congestion cost of $121.4 million reported by Transport Canada (2006 A), HOV/HOT lane deployment in the study area is able to reduce total Calgary congestion cost by 3.31%. This reduction in total congestion cost is called the “operating phase” impact of HOV/HOT lane implementation.

CHAPTER FOUR: EVALUATING THE ENVIRONMENTAL IMPACT OF DEPLOYING TRANSPORTATION STRATEGIES: CALGARY HOV/HOT LANE CASE STUDY

While simulation methods are widely utilized to assess the environmental impacts of transportation strategies, they have many limitations. Simulation-based methods are not suitable for large-scale analyses, as they are highly time-consuming and tedious exercises in modeling calibration and validation of a complete city network using simulation. This exercise becomes more challenging if the impacts are to be examined at the provincial/state or national level. Moreover, with sole reliance on simulation, these studies mainly consider emissions reduction from the operating phase, where only the potential GHG emission reduction from vehicle exhaust is considered. However, these short-term benefits are offset over the long-run by the induced demand generated by the travel-time reduction resulting from transportation improvements. In other words, these improvements can encourage more travel, which could lead to increases in travel demand, and therefore a rise in motor vehicle emissions.

The positive economic impact of transportation improvement resulting from the potential savings in total vehicular delays and total fuel consumption will affect other economic sectors, which may further use the transportation network to deliver their goods and services. In the long run, the resulting increase in vehicle-kilometers traveled may outweigh the potential emission and system efficiencies that are brought about by transportation improvement. Thus, depending on the structure of the economic sector in a given region, this may result in either an increase or a decrease in the GHG emissions of these economic sectors (the secondary phase). Overcoming these limitations necessitates a new evaluation approach that is capable of estimating both operating and secondary phase impacts at a city level.

This chapter applies Leontief's input-output (I-O) (Leontief, 1936) model that establishes the financial flow between industries to assess the large-scale environmental impacts of transportation strategies. The I-O model is an economy-wide model that can be utilized to evaluate the impact of any significant improvement in transportation networks at the regional level. Since the impacts of transportation strategies on the economic sectors are gradual, this framework is capable of predicting the direct and indirect long-term effects of transportation improvement on GHG emission levels. Moreover, this framework can be applicable to any transportation strategy and any region (i.e., national, provincial/state, and city levels) where an I-O model exists or can be estimated. It can also be used to estimate energy consumption and other types of emissions.

4.1 Overview and the Applied Framework

Leontief's input-output model is able to estimate the economic and environmental impact of any significant change in the economic sectors of the economy. Since transportation is considered as a separate sector in the transaction table, Leontief's input-output model can be applied to determine the impact of transportation policies and strategies on the total region's GHG emissions.

4.1.1 Overview of the Input-Output Model

The I-O model is an economic framework that shows the interdependence between different business and non-business sectors of an economy (Leontief, 1936), which is assumed to be composed of a finite number of commodities and industries with a certain amount of financial flow between each pair of industries or commodities. In this model, each industry uses input from itself or other industries to produce certain amount of outputs. These outputs may be used by other industries as their inputs or directly sold to final purchasers as a final product.

Every I-O model is composed of three elements: a transaction table, direct requirement table, and total requirement table. The transaction table shows the industry-commodity (or industry-industry) financial flow in terms of dollars in a certain period of time (usually a year). In the transaction table, each column shows the inputs, and each row shows the outputs of each specific sector. The basic assumption is that total input of an industry is equal to the total output of that industrial sector. A direct requirement table shows the amount of input that each industry needs directly from other industries to produce one unit of output. Based on this definition, a direct requirement table can be calculated by dividing the inputs of each industry by the total output of that industry. A total requirement table represents the required amount of inputs from other economic sectors for each industry (or commodity), both directly and indirectly, to produce one unit of output. The output of the industries (X) can be determined as:

$$X = AX + D \tag{4. 1}$$

Where:

A – Direct requirement table

D – Final demand for each sector ($)

Equation (4. 2) can be derived from equation (4.1) as:

$$X = (I - A)^{-1}D \tag{4. 2}$$

Where:

I – Identity matrix

$(I - A)^{-1}$ – Total requirement table

Equation (4. 2) determines the total required activity in an economy, both directly and indirectly, to meet a certain amount of final demand. In other words, based on the final demand for each commodity in an economy, the total required financial activity of each industry can be determined, in terms of dollars, to meet the demand with equation (4. 2).

I-O analysis can be used to evaluate the GHG emissions of a product, since there is a certain amount of GHG emissions associated with each economic activity in terms of producing goods or delivering services. Based on the amount of GHG emissions for each unit of output for each industry, the total GHG emitted to produce final demand is represented by equation (4. 3) (Hendrickson et al., 1998):

$$T = E(I - A)^{-1}D \tag{4. 3}$$

Where:

T – Total GHG emissions of the economy (Kt CO_2 eq.)

E – GHG emissions for each industry to produce one unit of output (Kt CO_2 eq. /$)

The advantage of I-O analysis in conducting an environmental assessment is that this method is capable of capturing all direct and indirect impacts, since it predicts changes in the overall economic activity as a result of any significant change in the local economy. Thus, the I-O model can prove to be an effective tool for realizing the effects of transportation strategies on the city-level economy and on city-level GHG emissions.

4.1.2 Transportation Strategies Impact: Operating and Secondary Phases

Evaluating the impact of transportation projects can be divided into two phases:

- The operating phase is comprised of short-term impacts that occur prior to travelers and economic sectors recognizing that the travel time has changed. In this phase, the improved travel time and traffic congestion reduction enhanced by transportation strategy decreases the GHGs emitted from motor vehicle exhaust.

- The secondary phase involves the long-term effects of the transportation improvements on changes in demand and on the economic sector. In this phase, the positive economic impacts (in terms of savings in total delayed time and fuel consumption savings) enhanced by transportation improvement affect other economic sectors, allowing industrial sectors to reinvest the savings in expanding the production of goods and services in the long-term. It is worth noting that 100% of the savings in this phase are assumed to be reinvested in production expansion, which is likely the case. This expansion will lead to increases in GHG emissions of the entire economy.

The decrease in total congestion cost implies that the economic sectors will be able to reinvest these savings into their production operations and increase their amount of outputs. Since the total supply includes both outputs by industries and the imports of goods and services, the total supply will increase.

The supply and demand balance is effectively achieved when:

- For industries, total inputs are equal to total outputs
- For products, total supply is equal to total demand

The supply-demand balance for the entire economy can be expressed as (Wild, 2013):

Outputs by industries + imports of goods and services = Inputs by industries + exports of goods and services + demand for final goods and services (by households and government)

Based on the supply-demand balance for industries, increasing the outputs results in the same level of increase for the inputs of industries. Simultaneously, this output growth will potentially increase exports and decrease the imports of goods and services. Therefore, for the supply-demand relation expressed above to remain balanced, the demand for final goods and services needs to be decreased.

Increase in the amount of output will increase the GHG emissions, and final demand reduction will reduce total GHG emissions of the economy. Hence, depending on the size of increases in supply and decreases in final demand, the GHG emissions of the total economy will either increase or decrease. We call this new phase the secondary phase. Evaluating the impact of the secondary phase is the major contribution of this chapter, which assists us to know whether or not implementing transportation strategy at the city level is beneficial in the long-term in terms of GHG emissions.

4.1.3 Applied Framework

In this section, the framework for determining the impact of the secondary phase is described. The proposed framework can be used to analyze any transportation strategy aiming to improve mobility and decrease traffic congestion, including intelligent transportation system techniques, congestion pricing, public transit, HOV/HOT and HOV lane implementation, etc.

The steps for the evaluation of the second phase impacts using I-O analysis are described in the following paragraphs:

Step 1: Calculate GHG emissions and congestion cost-savings of the operating phase

The impact of the operating phase can be determined using a vast array of methods. Collecting field data, microsimulation (similar to what was done in Chapter Three for HOV/HOT lane implementation in Deerfoot Trail) and macrosimulation are common methods to evaluate the operating phase impacts of transportation strategy. Congestion cost-savings can be obtained by adding up the monetized value of vehicular delay time and fuel saved due to implementing transportation strategy during a year.

Step 2: Evaluate city level economy GHG emissions before deploying transportation strategy

1) Calculate the national (provincial level in this study) direct requirement table by dividing the column input of each industry by the total output of that industry.

2) Construct the direct requirement table of the economy (city scale) by:

$$a_{ij} = LQ_i A_{ij} \tag{4. 4}$$

Where:

a_{ij} - Regional direct requirement table coefficients

A_{ij} - National (or provincial) direct requirement table coefficients

LQ_i - Location quotient of industrial sector i

Location quotient (LQ) is an analytical statistic that measures a region's industrial specialization relative to a larger geographic unit (usually the nation) (Bureau of Economic Analysis, 2008). For each industry, it can be calculated by:

$$LQ_i = \frac{RS_i}{TR} \div \frac{PS_i}{TP} \tag{4. 5}$$

Where:

RS_i - Regional salary of industry i ($)

TR - Total regional salary ($)

PS_i - Provincial salary of industry i ($)

TP - Total provincial salary ($)

It is important to note that the I-O model is accessible only for national and provincial levels. Hence, for impact analysis at the city level, we have to construct it.

3) Find the regional final demand by:

$$d_i = \alpha_i D_i \tag{4. 6}$$

Where:

d_i - Regional (city level) final demands ($)

D_i - Provincial final demands ($)

α_i - GDP ratio of industry i

The GDP ratio for each industry can be calculated using equation (4. 7):

$$\alpha_i = \frac{GDP_i^{reg}}{GDP_i^{pro}} \qquad (4.\ 7)$$

Where:

GDP_i^{reg} - Regional gross domestic products of industry i ($)

GDP_i^{pro} - Provincial gross domestic products of industry i ($)

GDP of industry i is the sum total of the market value of final goods and services of industry i produced during one year.

As with the I-O model, the final demand is usually reported for national and provincial levels, and is not available for the city level. Based on the definition of GDP, d_i can be a good estimate of final demand at the city level.

4) Calculate regional economy GHG emissions using equation (4. 3).

Step 3: Evaluate regional economy GHG emissions after deploying transportation strategy

1) Calculate the growth factor (GF) (Farooq et al., 2008) of the economic sectors from the congestion cost-savings in the transportation sector by:

$$GF_i = \frac{PO_{TW}}{PI_i} \times \frac{LQ_{TW}}{LQ_i} \times \%\ \text{operating phase effect} \qquad (4.\ 8)$$

Where:

GF_i – Growth factor of industry i

PO_{TW} -Total province transportation output ($)

PI_i – Total province input of industry i ($)

LQ_{TW} – Location quotient of transportation sector

GF is the percentage growth that implementing transportation strategy will bring for other economic sectors in the regional economy. The percentage operating phase effect in equation (4. 8) represents the percentage congestion cost-savings due to the operating phase.

2) Update the provincial transaction table incorporating growth factors by:

$$b_{ij} = B_{ij}(1 + GF_i) \qquad (4.\ 9)$$

Where:

b_{ij} – Updated province transaction table coefficient

B_{ij} - Basic province transaction table coefficient

Since we are only able to construct a regional direct requirement table (we cannot construct a regional transaction table from the national or provincial transaction table) and we need a regional transaction table to apply the operating phase impact in it, the idea represented in this study is first to evaluate the impact of transportation improvement at the provincial level and then localize this impact by constructing the regional direct requirement table from the updated provincial direct requirement table. Thus, in this way, the operating phase impact of deploying transportation strategy can be taken into consideration indirectly.

3) Calculate the updated provincial direct requirement table by dividing the column input of each industry in an updated provincial transaction table by the total output of that economic sector.
4) Construct the updated regional (city level) direct requirement table and the total requirement table from an updated provincial direct requirement table using equation (4. 4).
5) Update the provincial final demand by:

$$F_i^u = F_i^b - \sum_{j=1}^{n}(b_{ij} - B_{ij}) \qquad (4.\ 10)$$

Where:

F_i^u – Updated final demands for industry i ($)

F_i^b - Basic final demands for industry i ($)

$\sum_{j=1}^{n}(a_{ij} - A_{ij})$ in equation (4. 10) is growth in the input row sum of industry i.

As noted previously, deployment of a transportation strategy will increase the total supply of the economy. Moreover, for the supply-demand balance to remain balanced, the final demand for goods and services should be decreased. This is exactly what is done in this step. This amount of decrease in the final demand should be at the level in which the total input of industry i remains equal to the total output of industry i.

6) Calculate the updated regional final demand from updated provincial final demand using equation (4. 6).
7) Calculate total regional economy GHG emissions using equation (4. 3).
8) Calculate the secondary phase GHG emission changes by subtracting the total GHG emissions before deploying transportation strategy from the total GHG emissions after implementing transportation strategy.

$$SE = TGHG_2 - TGHG_1 \tag{4. 11}$$

Where:

SE – Emissions due to the secondary phase (Kt CO_2 eq.)

$TGHG_1$ – Total regional GHG emissions before deploying transportation strategy (Kt CO2 eq.)

$TGHG_2$ – Total regional GHG emissions after deploying transportation strategy (Kt CO2 eq.)

9) Determine the total GHG emission savings due to deploying transportation strategy by:

$$SGHG_T = SGHG_{Op} - SE \tag{4. 12}$$

Where:

$SGHG_T$ – Total regional GHG emission savings (Kt CO_2 eq.)

$SGHG_{Op}$ – Total regional GHG emissions savings due to the operating phase (Kt CO2 eq.)

Executing the applied framework introduced in this section results in determining the secondary phase impact of deploying any kind of transportation strategy.

4.2 Case Studies: Application of the Framework to the City of Calgary, Alberta, and the City of Edmonton, Alberta

In this section, the described framework is applied to evaluate the impact of deploying transportation strategy in the cities of Calgary and Edmonton, which are two major cities in Alberta, Canada. Edmonton is the capital of the province of Alberta, with a city area of 684.37 km^2 (Statistics Canada, 2014). Based on the 2011 census, the city has a population of 1,159,869, making it the second largest city in Alberta (Statistics Canada, 2014). The gross domestic product (GDP) of the Edmonton industrial sectors was 52,274 (in 2002 $M) in 2009 (The City of Edmonton, 2014), and the total Edmonton GHG emissions in 2008 were 18,200 $Kt\ CO_2\ eq.$ (Bow Valley Power, 2013).

The City of Calgary is the largest city in the province of Alberta, with an area of 825.29 km^2 (Statistics Canada, 2014) and a population of 1,214,839, based on the 2011 census (Statistics Canada, 2014). The GDP of Calgary's economic sectors was 67,417 (in 2002 $M) in 2009 (The City of Calgary, 2011). The total Calgary GHG emissions in 2008 were 16,060 $Kt\ CO_2\ eq.$ (The City of Calgary, 2010).

As can be seen, Calgary and Edmonton – two neighboring cities in the same province – are quite similar cities in terms of city area, population, GDP, and the total regional GHG emissions. The aim of these case studies is to determine the impact of different transportation strategies on regional GHG emissions. Indeed, a sensitivity analysis was conducted for both cities to compare the impact of deploying the same transportation strategies.

This necessitated the determination of the I-O model for the province of Alberta. The primary version of the Alberta I-O table consists of 32 rows and 32 columns (Statistics Canada, 2009). To better analyze the effects of transportation strategy, these 32 industries were aggregated into a fewer number of industries. A common type of aggregation is the two-digit North American industry classification system (NAICS), which combined the 32 industries into 18 major industries (Statistics Canada, 2013). However, since the GDP data of Calgary were not available for two-digit NAICS code, the industries were aggregated into 17 major industries for which the GDP data were available. The aggregation for the industries in Edmonton was done using NAICS code.

The aggregated industrial sectors for the City of Calgary and the City of Edmonton are shown in Table 4.1. Alberta transaction tables for the aggregated industries are shown in Tables 4.2 and 4.3.

Table 4. 1. Aggregated industrial sectors and related codes (left: Edmonton, right: Calgary)

Industrial Sector	Abbreviation	Industrial Sector	Abbreviation
Agriculture, forestry, fishing, and hunting	AFFH	Agriculture	Ag
Mining, quarrying, and oil and gas extraction	Mi	Forestry, fishing, mining, oil and gas	FFMOG
Utilities	U	Utilities	U
Construction	C	Construction	C
Manufacturing	Ma	Manufacturing	Ma
Wholesale trade	WT	Wholesale trade	WT
Retail trade	RT	Retail trade	RT
Transportation and warehousing	TW	Transportation and Warehousing	TW
Information and cultural industries	IC	Finance and insurance, real estate, and rental and leasing	FIRRL
Finance and insurance, real estate, and rental and leasing	FIRRL	Professional, scientific, and technical services	PST
Professional, scientific, and technical services	PST	Management, administrative, and other support	MAS
Administrative and support, waste management, and remediation services	AWR	Educational services	ES
Educational services	ES	Healthcare and social assistance	HS
Healthcare and social assistance	HS	Information, culture, and recreation	ICR
Arts, entertainment, and recreation	AER	Accommodation and food services	AF
Accommodation and food services	AF	Other services (except public administration)	OP
Other services (except public administration)	OP	Public administration	P
Public administration	P		

Table 4. 2. Alberta symmetric I-O table including 18 industries ($M)

	AFFH	Mi	U	C	Ma	WT	RT	TW	IC	FIRRL	PST	AWR	ES	HS	AER	AF	OP	P
AFFH	3584	56	13	109	5234	10	6	64	2	5	15	2	0.033	4	2	129	5	188
Mi	39	5879	763	4970	11325	191	100	73	15	194	34	13	5	12	2	15	15	254
U	189	989	17	64	1066	65	104	149	19	318	39	15	8	33	11	77	45	406
C	178	991	306	92	204	109	161	318	25	1563	72	44	4	18	17	147	33	1165
Ma	2887	7533	237	11884	15288	834	569	2227	536	1008	1050	666	20	424	241	1740	584	3196
WT	374	1868	70	1590	1850	340	242	237	87	248	345	146	5	97	52	286	119	842
RT	126	274	11	502	429	263	183	138	62	141	225	106	4	80	111	393	90	725
TW	348	1241	68	764	2496	857	360	2835	141	519	437	216	13	96	42	100	152	952
IC	102	479	48	174	233	405	373	211	1049	988	575	276	13	164	53	207	151	666
FIRRL	521	5604	198	1890	1723	1197	2087	1060	375	6846	1177	520	75	314	154	858	401	1177
PST	326	3697	105	2886	543	730	666	278	231	1835	2523	459	10	101	49	164	167	1925
AWR	46	1968	51	452	487	512	421	347	235	1754	714	311	19	95	81	192	240	1467
ES	0.092	12	1.5	16	1	5	6	2	3	14	10	10	1	38	1	8	8	131
HS	0.002	1	0.113	0	1	1.4	0.75	0.124	0.077	10	0.126	0.05	0.157	2.5	0.004	0.085	0.025	4176
AER	6	23	1.71	14	32	32	47	11	50	39	34	20	1.36	5	76	46	17	106
AF	22	121	4.34	44	135	79	120	185	64	190	304	128	7	62	55.33	79.3	97	400
OP	71	378	10	153	147	21	19	174	26	294	230	140	7	126	65	70	86	408
P	81	258	9	127	185	163	177	101	72	397	215	66	12	86	49	72	60	1665
Total	11347	82995	5865	47543	57291	17413	16337	18610	9041	52463	20857	8817	527	6677	2256	9788	6119	51999

Table 4. 3. Alberta symmetric I-O table including 17 industries ($M)

	Ag	FFMOG	U	C	Ma	WT	RT	TW	FIRRL	PST	MAS	ES	HS	ICR	AF	OP	P
Ag	3139	42	2	92	4,643	6	3	34	1	12	0	0	4	2	123	4	49
FFMOG	216	6162	774	4987	11916	196	103	103	198	36	14	5	12	18	20	16	393
U	184	994	17	64	1066	65	104	149	318	39	15	8	33	30	77	45	406
C	171	999	306	92	204	109	161	318	1563	72	44	4	18	42	147	33	1165
Ma	2725	7694	237	11884	15288	834	569	2227	1008	1050	666	20	424	777	1740	584	3196
WT	348	1894	70	1590	1850	340	242	237	248	345	146	5	97	139	286	119	842
RT	116	284	11	502	429	263	183	138	140	225	106	4	80	174	393	90	725
TW	294	1294	68	764	2496	857	360	2835	519	437	216	13	96	184	100	152	952
FIRRL	466	5659	198	1890	1723	1197	2087	1060	6846	1177	520	75	314	529	858	401	1177
PST	310	3712	105	2886	543	730	666	278	1835	2523	459	10	101	279	164	167	1925
MAS	37	1977	51	452	487	512	421	347	1754	714	311	19	95	316	192	240	1467
ES	0	12	1	16	1	5	6	2	14	10	10	1	38	3	8	8	131
HS	0	1	0	0	1	1	1	0	10	0	0	0	2	0	0	0	4176
ICR	100	510	49	188	264	438	420	223	1027	609	296	14	170	1227	253	168	772
AF	19	124	4	44	135	79	120	185	190	304	128	7	62	119	79	97	400
OP	53	396	10	153	147	21	19	174	294	230	140	7	126	91	70	86	408
P	75	264	9	127	185	163	177	101	397	215	66	12	86	121	72	60	1665
Total	10244	84098	5865	47543	57291	17413	16337	18610	52463	20857	8817	527	6677	11297	9788	6119	51999

4.2.1 Secondary Phase Impact of Deploying HOV/HOT Lanes in Deerfoot Trail, Calgary

As discussed previously in Chapter One, implementing any kind of transportation strategy aiming to mitigate congestion has two different impacts:

- Operating phase
- Secondary phase

During the operating phase, reducing congestion in the transportation network leads to a decrement in the GHG emitted from vehicle exhaust. This will result in a reduction in total regional congestion cost in the short-term. However, in the long-term, induced travel demand resulting from increases in the production of the goods and services may outweigh the potential GHG emission reduction of the operating phase. The aim of this section is to evaluate the secondary phase impact of deploying HOV/HOT lanes in Deerfoot Trail (discussed in Chapter Three) to determine feasibility from the environmental perspective.

The framework introduced at the beginning of this chapter can be applied to determine the impact of the HOV/HOT lane deployment in Calgary as follows:

Step 1: Calculate GHG emissions and congestion cost-savings of the operating phase

The operating phase impact of deploying HOV/HOT lanes was evaluated in Chapter Three. The results showed that HOV/HOT lane implementation decreased total Calgary GHG emissions and congestion costs by 2,742.1 tonnes CO_2 eq. and 3.38%, respectively.

Step 2: Evaluate regional economy GHG emissions before deploying transportation strategy

Based on Alberta direct requirement table and LQ values from Table 4.4 (calculated with equation [4. 5]), the Calgary direct requirement table was calculated using equation (4.4) (Table 4.5). Since the Calgary direct requirement table was constructed from the Alberta one, the LQ values for

Calgary relative to Alberta were required. Although this information was not directly available, it can be calculated with equation (4. 13):

$$LQ(CAL/AB) = \frac{LQ(CAL/CAN)}{LQ(AB/CAN)} \qquad (4.\ 13)$$

Where:

$LQ(CAL/AB)$ – The location quotient of Calgary relative to Alberta

$LQ(CAL/CAN)$ – The location quotient of Calgary relative to Canada

$LQ(AB/CAN)$ – The location quotient of Alberta relative to Canada

The $LQ(AB/CAN)$ values in Table 4.4 were calculated using equation (4. 5).

Finally, using equation (4. 3), total Calgary GHG emissions before deploying HOV/HOT lanes in Deerfoot Trail are calculated.

$$\text{Total Calgary GHG emissions} = 13865.1 \text{ Kt } CO_2 \text{ eq.}$$

Since the information used for evaluating matrix E in equation (4. 3) excludes household GHG emissions, the GHG emissions calculated above are slightly lower than the current Calgary GHG emissions of $16561 \text{ Kt } CO_2 \text{ eq.}$ (The City of Calgary. 2010). Considering household emissions, Calgary GHG emissions are:

$$TGHG_1 = GHG_{wH} + (GHG_{NH} \times GHGshare_{CAL}) \qquad (4.\ 14)$$

Where:

$TGHG_1$ – Total Calgary GHG emissions including households before HOV/HOT deployment (Kt CO2 eq.)

GHG_{wH} – Total Calgary GHG emissions excluding households before HOV/HOT deployment (Kt CO2 eq.)

GHG_{NH} – Total national household emissions (Kt CO2 eq.)

$GHGshare_{CAL}$ – Calgary share of total national emissions

Considering 0.0264 as the Calgary GHG emission share of the national emissions (689,000 Kt CO_2 eq. in 2009) (Environment Canada, 2014) and 113,973 as the total national household emission per Kt CO_2 eq. (Statistics Canada, 2012) total Calgary GHG emissions were calculated using equation (4. 14) as follows:

$$\mathrm{TGHG}_1 = 13{,}865.1 + (113{,}973 \times 0.0240) = 16{,}604.56\ \mathrm{Kt\ CO_2\ eq.}$$

Comparing the model's prediction with the actual Calgary GHG emissions $(16561\ \mathrm{Kt\ CO_2\ eq.})$, it is revealed that this model is capable of providing precise estimation.

Step 3: *Evaluate regional economy GHG emissions after deploying transportation strategy*

Implementation of the proposed HOV/HOT lane in Calgary could decrease the total congestion cost by 3.31%. As noted previously, it will lead to expansion of the economic sectors. The magnitude of this expansion can be expressed in growth factor (GF). To incorporate the impact of GF into the Alberta transaction table, the row output of each industry should be multiplied by (1+GF). Since the changes of each industry are considered endogenous, the coefficient of that industry should remain unchanged. This means that, when updating the Alberta transaction table, the main diagonal should not be changed. After updating the Alberta direct requirement table, the Calgary direct requirement table is updated (Table 4.6). The Calgary final demand for each sector can be calculated by multiplying the updated Alberta final demand by the GDP ratio of each industry. Using equation (4. 3), the total Calgary GHG emissions after deploying HOV/HOT lane are:

$$\mathrm{TGHG}_2 = 16{,}605.48\ \mathrm{Kt\ CO_2\ eq.}$$

$$\text{Secondary phase impact} = 16{,}605.48 - 16{,}604.56 = +0.93\ \mathrm{Kt\ CO_2\ eq.}$$

Using equation (4. 12):

$$\text{Total GHG savings} = 2.74 - 0.93 = 1.82 \text{ Kt } CO_2 \text{ eq.}$$

The operating phase GHG emission savings are $2{,}742.1 \text{ tonnes } CO_2 \text{ eq.}$ which is equivalent to $2.74 \text{ Kt } CO_2 \text{ eq.}$ Analysis has shown that implementing HOV/HOT lanes in Calgary can decrease total GHG emissions by $1.82 \text{ Kt } CO_2 \text{ eq.}$, considering both operating and secondary phases, which is lower than the operating phase savings. Moreover, it has been proven that by considering even the GHG emission increase due to the secondary phase, HOV/HOT lane deployment is beneficial from an environmental perspective.

Table 4. 4. Economic and emission data of the City of Calgary

Sector	National Emission (Kt CO_2)	AB GDP ($M)	Calgary GDP ($M) (The City of Calgary, 2011)	GDP Ratio	AB Final Demand ($M)	Calgary Final Demand ($M)	Emission (Kt CO_2/$)	LQ (CAL/CAN) (The City of Calgary, 2011)	LQ (AB/CAN)	LQ (CAL/AB)	GF
Ag	67617	4494	993	0.221	2087	461.1	0.718	0.7	0.877	0.798	0.052
FFMOG	125742	33790	11661	0.345	58929	20336.7	0.104	3.46	3.894	0.889	0.004
U	118582	3761	1428	0.380	2248	853.7	1.280	0.91	1.072	0.849	0.044
C	12403	12742	5141	0.403	42097	16984.5	0.016	1.38	1.530	0.902	0.006
Ma	110553	13015	4862	0.374	6369	2379.3	0.124	0.64	0.657	0.975	0.006
WT	11763	8735	3005	0.344	8613	2963.1	0.047	0.97	0.974	0.996	0.018
RT	7953	9132	3027	0.331	12476	4135.7	0.035	0.92	0.923	0.997	0.019
TW	76074	9157	3808	0.416	6973	2899.8	0.236	1.17	1.001	1.168	0.033
FIRRL	19029	30073	13139	0.437	26287	11485.1	0.020	0.98	0.845	1.160	0.006
PST	1920	9337	5147	0.551	4165	2296.1	0.004	1.42	1.217	1.167	0.014
MAS	3162	3817	1646	0.431	298	128.5	0.020	0.91	0.804	1.132	0.043
ES	311	7288	2414	0.331	261	86.5	0.043	0.83	0.737	1.127	0.726
HS	2352	9267	3147	0.340	2484	843.3	0.025	0.86	0.975	0.882	0.042
ICR	1468	6172	2834	0.459	4570	2098.4	0.007	1.08	0.689	1.567	0.03
AF	1914	3963	1397	0.353	7692	2711.6	0.013	0.86	1.015	0.847	0.034
OP	8386	4565	1611	0.353	3695	1303.9	0.093	1.04	1.121	0.928	0.052
P	21227	7326	2130	0.291	48204	14015.8	0.034	0.58	0.711	0.816	0.007

Table 4. 5. Calgary direct requirement table

	Ag	FFMOG	U	C	Ma	WT	RT	TW	FIRRL	PST	MAS	ES	HS	ICR	AF	OP	P
Ag	0.245	4E-04	2E-04	0.002	0.065	3E-04	1E-04	0.001	2E-05	5E-04	3E-05	9E-06	4E-04	2E-04	0.01	6E-04	8E-04
FFMOG	0.019	0.065	0.117	0.093	0.185	0.01	0.006	0.005	0.003	0.002	0.001	0.008	0.002	0.001	0.002	0.002	0.007
U	0.015	0.01	0.003	0.001	0.016	0.003	0.005	0.007	0.005	0.002	0.001	0.013	0.004	0.002	0.007	0.006	0.007
C	0.015	0.011	0.047	0.002	0.003	0.006	0.009	0.015	0.027	0.003	0.004	0.006	0.002	0.003	0.014	0.005	0.02
Ma	0.259	0.089	0.039	0.244	0.26	0.047	0.034	0.117	0.019	0.049	0.074	0.037	0.062	0.067	0.173	0.093	0.06
WT	0.034	0.022	0.012	0.033	0.032	0.019	0.015	0.013	0.005	0.016	0.017	0.009	0.014	0.012	0.029	0.019	0.016
RT	0.011	0.003	0.002	0.011	0.007	0.015	0.011	0.007	0.003	0.011	0.012	0.007	0.012	0.015	0.04	0.015	0.014
TW	0.034	0.018	0.014	0.019	0.051	0.057	0.026	0.178	0.012	0.024	0.029	0.028	0.017	0.019	0.012	0.029	0.021
FIRRL	0.053	0.078	0.039	0.046	0.035	0.08	0.148	0.066	0.151	0.065	0.068	0.166	0.055	0.054	0.102	0.076	0.026
PST	0.035	0.052	0.021	0.071	0.011	0.049	0.048	0.017	0.041	0.141	0.061	0.022	0.018	0.029	0.02	0.032	0.043
MAS	0.004	0.027	0.01	0.011	0.01	0.033	0.029	0.021	0.038	0.039	0.04	0.042	0.016	0.032	0.022	0.044	0.032
ES	0	2E-04	3E-04	4E-04	1E-05	3E-04	4E-04	1E-04	3E-04	5E-04	0.001	0.002	0.006	3E-04	9E-04	0.001	0.003
HS	2E-07	9E-06	2E-05	0	1E-05	7E-05	4E-05	6E-06	2E-04	5E-06	5E-06	3E-04	3E-04	6E-06	8E-06	4E-06	0.071
ICR	0.015	0.01	0.013	0.006	0.007	0.039	0.04	0.019	0.031	0.046	0.053	0.043	0.04	0.17	0.04	0.043	0.023
AF	0.002	0.001	6E-04	8E-04	0.002	0.004	0.006	0.008	0.003	0.012	0.012	0.011	0.008	0.009	0.007	0.013	0.007
OP	0.005	0.004	0.002	0.003	0.002	0.001	0.001	0.009	0.005	0.01	0.015	0.012	0.017	0.007	0.007	0.013	0.007
P	0.006	0.003	0.001	0.002	0.003	0.008	0.009	0.004	0.006	0.008	0.006	0.018	0.01	0.009	0.006	0.008	0.026

Table 4. 6. Updated Calgary direct requirement table

	Ag	FFMOG	U	C	Ma	WT	RT	TW	FIRRL	PST	MAS	ES	HS	ICR	AF	OP	P
Ag	0.245	4E-04	2E-04	0.002	0.068	3E-04	2E-04	0.001	2E-05	5E-04	3E-05	1E-05	5E-04	2E-04	0.011	6E-04	8E-04
FFMOG	0.019	0.065	0.118	0.094	0.186	0.01	0.006	0.005	0.003	0.002	0.001	0.008	0.002	0.001	0.002	0.002	0.007
U	0.016	0.01	0.003	0.001	0.017	0.003	0.006	0.007	0.005	0.002	0.002	0.013	0.004	0.002	0.007	0.007	0.007
C	0.015	0.011	0.047	0.002	0.003	0.006	0.009	0.015	0.027	0.003	0.005	0.006	0.002	0.003	0.014	0.005	0.02
Ma	0.261	0.09	0.04	0.245	0.26	0.047	0.034	0.113	0.019	0.049	0.074	0.037	0.062	0.068	0.174	0.094	0.06
WT	0.035	0.023	0.012	0.034	0.033	0.019	0.015	0.013	0.005	0.017	0.017	0.009	0.015	0.013	0.03	0.02	0.016
RT	0.011	0.003	0.002	0.011	0.008	0.015	0.011	0.007	0.003	0.011	0.012	0.007	0.012	0.016	0.041	0.015	0.014
TW	0.035	0.019	0.014	0.019	0.053	0.059	0.027	0.178	0.012	0.025	0.03	0.029	0.017	0.02	0.012	0.03	0.022
FIRRL	0.053	0.079	0.039	0.046	0.035	0.08	0.149	0.064	0.151	0.066	0.069	0.167	0.055	0.055	0.102	0.076	0.026
PST	0.036	0.052	0.021	0.072	0.011	0.05	0.048	0.017	0.041	0.141	0.062	0.023	0.018	0.029	0.02	0.032	0.044
MAS	0.004	0.028	0.01	0.011	0.01	0.035	0.03	0.021	0.04	0.04	0.04	0.044	0.017	0.033	0.023	0.046	0.033
ES	0	3E-04	5E-04	6E-04	2E-05	5E-04	8E-04	2E-04	5E-04	9E-04	0.002	0.002	0.011	5E-04	0.002	0.002	0.005
HS	2E-07	1E-05	2E-05	0	2E-05	7E-05	4E-05	6E-06	2E-04	6E-06	5E-06	3E-04	3E-04	7E-06	8E-06	4E-06	0.074
ICR	0.016	0.01	0.014	0.006	0.007	0.041	0.042	0.019	0.032	0.047	0.054	0.044	0.041	0.17	0.042	0.044	0.024
AF	0.002	0.001	6E-04	8E-04	0.002	0.004	0.006	0.008	0.003	0.013	0.013	0.012	0.008	0.009	0.007	0.014	0.007
OP	0.005	0.005	0.002	0.003	0.003	0.001	0.001	0.009	0.005	0.011	0.016	0.013	0.018	0.008	0.007	0.013	0.008
P	0.006	0.003	0.001	0.002	0.003	0.008	0.009	0.004	0.006	0.008	0.006	0.019	0.011	0.009	0.006	0.008	0.026

4.2.2 Sensitivity Analysis

As discussed previously in Chapter Three, the more is the congestion cost-savings, the more is the GHG emission savings. This is an interesting finding, especially from transportation policy-makers' perspective. By considering only the short-term impact (the impact of operating phase), they tend to choose and implement those strategies that have the maximum impact in total congestion cost. However, does this fact also hold true for the long-term? In other words, would concentrating only on reducing traffic congestion lead to decreasing GHG emissions in the long-term? Answering this question necessitates recognizing the behavior of the secondary phase impact in regards to the total congestion cost-savings.

To better answer this question, a sensitivity analysis was conducted for the City of Calgary and the City of Edmonton, considering the impact of variation in the congestion cost-savings enhanced by the operating phase on total regional GHG emission savings. In Fig. 4.1, the red curve represents the impact of the operating phase, assuming a linear relationship between GHG emissions and total congestion cost; the blue curve shows the total impact that incorporates both the short-term direct (the operating phase) and long-term indirect (the secondary phase) effects.

Since the red curve considers only GHG emission reduction from vehicle exhaust, assuming fixed travel demand, it tends to overestimate GHG emission savings. As can be seen in Fig. 4.1, consideration of the impact of the secondary phase results in consistently lower actual GHG savings.

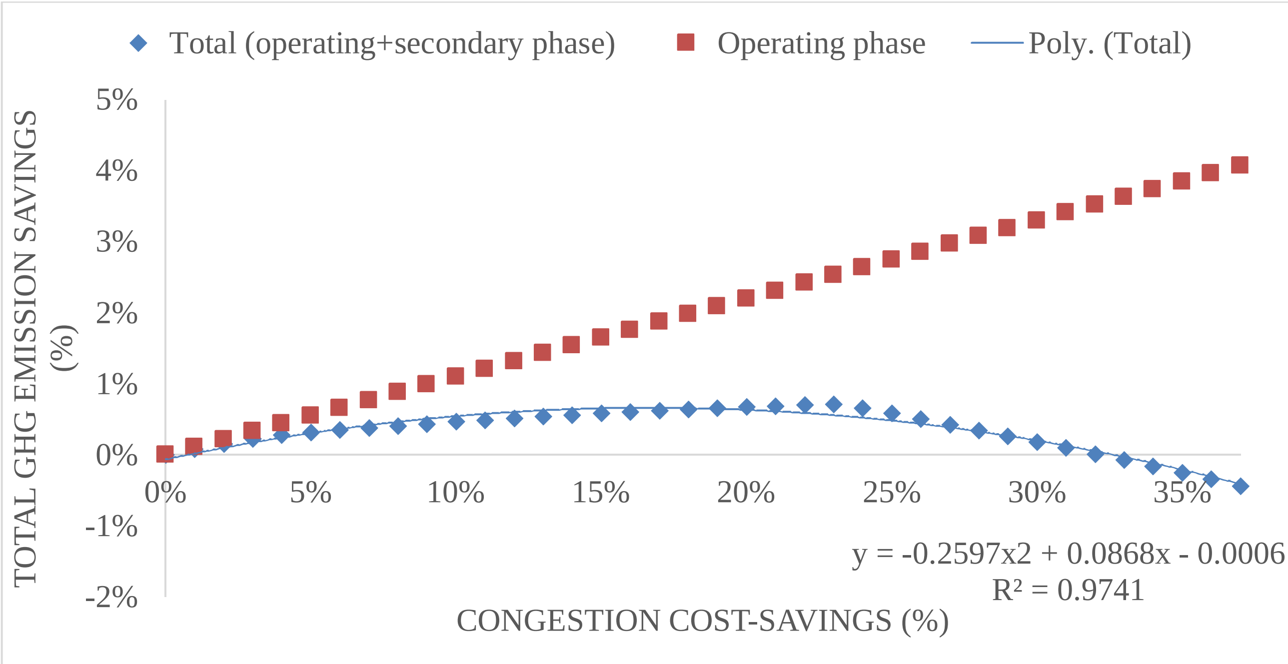

Figure 4. 1. Sensitivity analysis for Edmonton

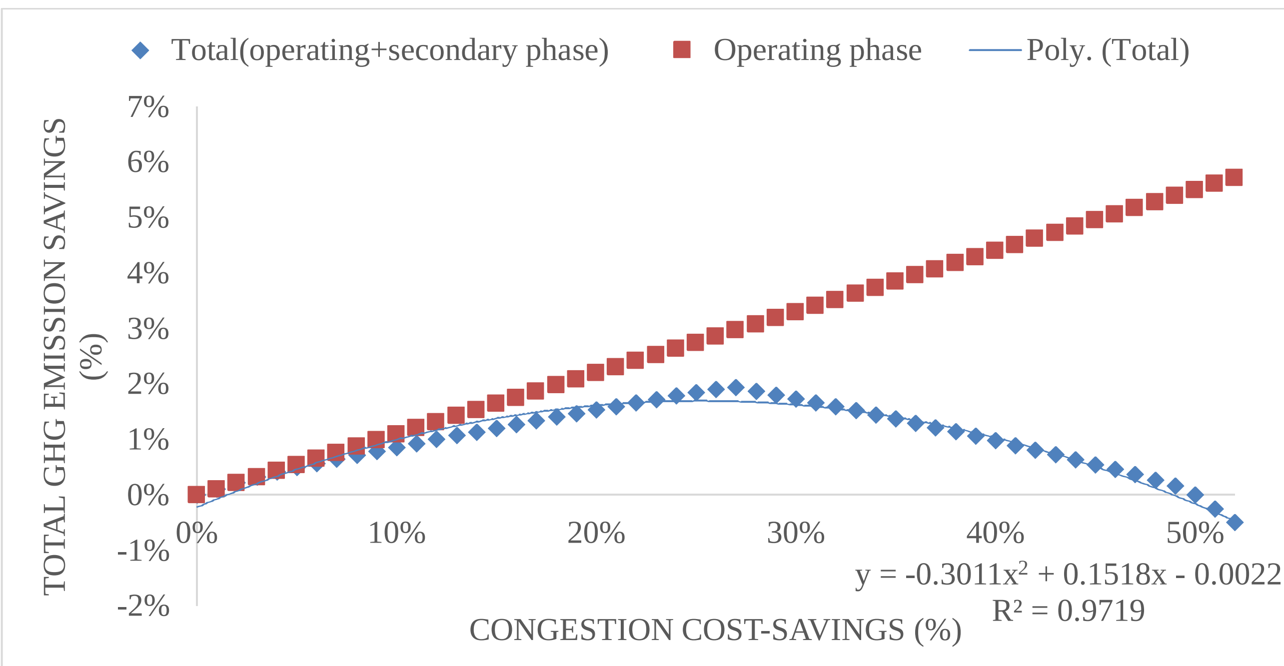

Figure 4. 2. Sensitivity analysis for Calgary

From Fig. 4.1, it can be concluded that below the point corresponding to 23% congestion reduction, the amount of operating phase GHG emission savings is greater than the increase in GHG emissions due to the secondary phase. However, the results are non-linear and can be expressed by the following quadratic equation:

$$TGHGS = -0.2597CS^2 + 0.0868CS - 0.0006 \qquad (4.\ 15)$$

Where TGHGS is the total Edmonton GHG emission savings percentage, and CS is the operating phase congestion cost-savings.

The GHG emission savings will reach an optimal GHG reduction for the point corresponding to 23% congestion cost-savings. Beyond this point, the percentage of GHG reduction starts decreasing and even becomes negative (i.e., resulting in more GHG emissions) when the congestion cost-savings increase to more than 32%. This implies that by increasing the operating phase impact, the growth rate of the secondary phase impact will exceed that of the operating phase, and consequently lead to decreased GHG savings. This may be attributed to the anticipated massive industrial expansion resulting from the significant reduction in the transportation sector's congestion costs, as reflected in the I-O analysis table.

Transportation costs are, in fact, a major contributor to overall product costs, ranging from 4% to 57% of the product cost depending on the industry sector (Tompkins Supply Chain Consortium, 2012). In addition, transportation is the second largest expenditure for households, corresponding to 19% of total household expenditures (Center for Transit Oriented Development, 2008). Such household spending is indirectly included as a major input of industrial sectors in the I-O table, varying from 15% to 44% of total inputs, depending on the industry sector (Statistics Canada, 2009). Thus, a sizable reduction in congestion costs will result in a decrease in the total cost of industrial inputs, in terms of hourly wages and salaries paid and the final price of sale (output) simultaneously. Since the output of each industry in the I-O table is an input of another industry, it would, in turn, decrease the total input cost of all industrial sectors. This significant savings in the cost of inputs, including both wages and salaries paid to households and paid to other industries, to purchase their outputs, along with the massive decrease in transportation costs, in terms of goods and services delivery costs, can be reinvested to expand production. This economic improvement will, in turn, result in additional emissions that would offset emission reduction resulting from the operating phase.

It is important to note that, in this study, it is assumed that 100% of this savings would be reinvested for production expansion, which is likely the case. Since this long-term trend would lead to an increase in total GHG emissions, it is necessary to deploy additional green policies, such as carbon tax, carbon capture, and industrial shift from traditional fossil fuels to green technologies. These policies in the long-term are expected to have an impact on reversing the anticipated trend by changing matrixes A and E in equation (3).

Although a similar trend was obtained for Calgary (Fig. 1[b]), there were some differences between these two cases. First, for Calgary, the reported GHG emission savings in the interval (0%, 10%) were closer to the red curve, indicating that the impact of the secondary phase for this interval was negligible. Second, the maximum Calgary GHG emission savings were 322.1 Kt CO_2 eq. at 27%, which is roughly 2.5 times more than that of Edmonton (130.1 Kt CO_2 eq. at 23%). The reason for this is that the LQ values for most industrial sectors of Edmonton are greater than the same industries in Calgary. In other words, based on the GF definition, the potential growth of those industries is expected to be much greater for Edmonton. This suggests that deploying the same strategy in both cities can affect the economic sectors of Edmonton more significantly and induce further increases in its industrial operations. Therefore, the secondary phase GHG emission increment is greater for Edmonton, while the operating phase

GHG emission savings of both cities are roughly equal. This finding suggests that the impact of even the same strategy can vary drastically from one city to another. Moreover, for the same level of congestion cost-savings, the total Calgary GHG emission savings were greater than those of Edmonton. Finally, the point at which GHG savings were zero for Calgary corresponded to 50% congestion reduction, while it corresponded to only a 32% congestion reduction for Edmonton. These findings reveal that deploying similar transportation strategies aimed at mitigating traffic congestion would more effective, in terms of emission savings, in Calgary. This analysis can help provinces determine what and where projects should be prioritized.

CHAPTER FIVE:SUMMARY AND CONCLUSIIONS

This research mainly focuses on evaluating the environmental impact of implementing HOV/HOT lanes in Deerfoot Trail, Calgary. Although there is no HOV/HOT lane implemented in Calgary presently, it has been considered as an effective ITS tool to mitigate traffic congestion on freeways during rush hours. This study consists of two major parts:

5.1 Research Summary and Contributions

5.1.1 HOV/HOT Model and Evaluating the Operating Phase Environmental Impact

A new approach was taken to model the HOV/HOT lane implementation, and the performance of the proposed model was tested in QUADSTONE PARAMICS microsimulation package to assess its operating phase environmental impact. In the operating phase, the GHG emission from the vehicles' exhaust during HOV/HOT operation is only considered. The probe vehicles and point detectors were used to collect the average speed and traffic flow from the motorway, and the Newell triangular traffic model was adopted to represent the current and future traffic state on the motorway predicted by the METANET model. Minimizing total passenger travel-time was chosen as the main objective function of the HOV/HOT model, and the toll rate at each time step was determined consequently.

The main findings of this part are outlined below:

- HOV/HOT implementation on 7.5 km of the Deerfoot Trail is able to improve total network travel-time by 1.69%.
- The emissions of oxides of nitrogen, particulate matter, C02 and CO were reduced by 3.44%, 1.84%, 1.66%, and 0.86% respectively. However, hydrocarbon emissions increased slightly by 0.22%.

- The new HOV/HOT lane saves 344,978.9 L of gasoline in the simulated network per year, which indicates a 1.66 % improvement in total network fuel consumption.
- Total Calgary congestion costs will be decreased by 3.31% due to the proposed HOV/HOT model.

5.1.2 Environmental Input-Output Analysis for Evaluating the Secondary Phase Environmental Impact

In this part, an environmental input-output analysis framework was developed to estimate total GHG emission savings of the HOV/HOT lane implementation. However, the presented framework is capable of estimating the long-term environmental impact of any transportation improvement strategy aiming to mitigate traffic congestion at the city, provincial/state, or national level. The analysis showed that, by implementing HOV/HOT lanes, the impacts are not restricted to the transportation sector and involve all other industries in a regional economy.

The presented framework was applied to two case studies – Edmonton and Calgary – two cities in the province of Alberta, Canada. The major findings of the analysis are outlined below:

- While transportation improvements can potentially decrease the GHG emissions of a transportation network during the operating phase, the GHG emissions of the secondary phase may increase in the long-term.
- Since the relationship between GHG emission savings and congestion cost-savings from the operating phase and secondary phase are linear and quadratic, respectively, the results show that a high reduction in regional congestion costs that can be achieved through localized transportation improvement can even result in a negative impact in terms of GHG emissions in the long-term.
- The focus on congestion reduction alone cannot meet the requirement of reducing GHG

emissions in the long-term. This finding is contrary to the general belief that considers only the impact of the operating phase.

- This framework can be used as a decision support tool to help transportation policy-makers prioritize strategies that are able to simultaneously reduce congestion and large-scale GHG emissions in the long-term, in order to obtain a balanced trade-off between these performance indicators.
- The sensitivity analysis revealed the different impacts that different regional economic structures have on the level of GHG emissions.
- Deploying transportation strategies that result in similar congestion reductions in two cities in the same province with similar governmental systems and cultural characteristics can lead to significantly different levels of GHG emission savings.
- The magnitude of the secondary phase impact is greater for more industrialized cities (cities with higher LQ values). This implies that, for a wider range of congestion cost-savings, GHG emission savings of less industrialized cities (cities with lower LQ values) will remain positive. Consequently, it can be interpreted that a broader variety of transportation policies and strategies with different impacts on congestion cost reduction can be deployed in less industrialized cities. This key finding enables transportation decision-makers at the provincial level to prioritize the cities in which transportation strategies is going to be implemented and to choose the proper strategy with maximum benefit in terms of reducing GHG emission and congestion levels.

5.1.3 Research Contributions

The contributions of this study are outlined below:

- Developing a new HOV/HOT modelling approach in order to minimize the total number of passengers travelling on the examined network.
- Defining the terms, operating phase and the secondary phase, to represent the different impacts of deploying transportation strategies.
- Evaluating the long-term environmental impact of deploying HOV/HOT lanes using Leontief Input-Output (I-O) analysis. To the best of the authors' knowledge, this study is the first attempt to assess the environmental impact of a transportation strategy using I-O analysis.
- Reconstructing Calgary and Edmonton I-O models using the Alberta I-O model.
- Conducting a large-scale sensitivity analysis to evaluate the impact of congestion cost-savings (enhanced by the operating phase) on long-term regional GHG emissions for two case studies, i.e., the City of Calgary and the City of Edmonton.

5.1.4 Future Works and Recommendations

In addition to the effectiveness of the proposed model in elucidating the impact of transportation strategies in the long-term and on a large scale, this model has a limitation. One of the limitations of the study is that it did not include a behavioral model to examine the impact of the presence of an HOV/HOT on the propensity of travelers to car pool. This can be addressed in the future through a combination of Revealed preference (RP) and Stated preference (SP) questions on traveler's perception towards HOV/HOT lane facility and attitude towards carpooling. Questions related to potential factors that will encourage carpooling, ride sharing and public transit and the willingness of SOV travelers to pay for toll need to be included in the survey.

In addition, the safety impact of HOV/HOT needs also to be examined on future studies. In addition, more sensitivity analysis needs to be conducted to examine the impact of various vehicle composition and network congestion levels on the performance of HOV/HOT approach. Another major assumptions in this study was the use of the I-O model for 2009 in the analysis, assuming that it would not change significantly over the next few years. As an extension of this research, an advanced economic tool can be used to predict the regional I-O model for upcoming years. This can be considered as a topic of future study.

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APPENDIX

The modified Deerfoot Trail model in PARAMICS along with the PARAMICS API code developed for this study, can be find in the CD-ROM attached to the thesis.