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Modeling truck toll competition between two cross-border bridges under various regimes

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MODELING TRUCK TOLL COMPETITION BETWEEN TWO CROSS-BORDER BRIDGES UNDER VARIOUS REGIMES

By

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ABSTRACT

The competition between a new publicly-owned cross-border bridge and the existing Ambassador Bridge is modeled in this thesis as a duopoly game where each bridge's strategy is its toll level. We assume the Ambassador Bridge always wants to maximize its profit, while the new bridge may have various objective functions. The competition between the two bridges has a natural bi-level structure, with the upper level being the two bridges setting their respective tolls, and the lower level being the road users choosing their routes. The competition equilibrium (i.e. Nash equilibrium) emerges when each bridge cannot improve its objective function by unilaterally changing its truck toll level. The Mesh Method is employed to solve this bi-level equilibrium problem in a simulation context. The obtained results of different competition regimes provide valuable insights about the nature of the toll competition that will likely emerge in the future.

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INTRODUCTION

1.1 <u>The Research Problem</u>

Cross-border transportation plays an increasingly crucial role in the trade relations of neighboring countries. The analysis of traffic flows across international borders usually requires a well-defined modeling framework capable of examining new transportation policies. The latter are important in regions of high cross-border traffic activities such as Canada and the United States. The border separating Canada and the United States is the longest international border worldwide. It spans across eight Canadian Provinces and thirteen U.S. states and as such, supports the largest bilateral trade relationship around the world (McEwen, 2001).

Among all the crossings between Canada and the United States, the one located along the Detroit River between Windsor, Ontario and Detroit, Michigan handles a significant amount of daily bilateral trade (Anderson, 2012). The majority of this trade is handled by trucks via the Ambassador Bridge connecting Windsor to Detroit.

In order to promote bilateral trade and enhance the economic growth of both countries, a new publicly owned bridge between Windsor and Detroit, named Detroit River International Crossing (DRIC), is announced to be completed over the next several years. The DRIC will facilitate the movement of people and goods across the border in the future and will ensure sufficient border crossing capacity. Also, the DRIC is expected to boost cross-border trade and traffic demand between Canada and the US.

The development of the DRIC Bridge will affect the nature of traffic flows and toll prices on the transportation facilities connecting Windsor to Detroit. However, determining the nature of the emerging new traffic flow and toll prices is not a trivial task. Therefore, it is necessary to develop a modeling framework capable of simulating cross-border traffic and toll prices for both the Ambassador Bridge and the DRIC Bridge. Such framework must be able to handle the estimation of tolls under various collaboration and/or competition regimes. This is particularly important since the Ambassador Bridge is privately owned while the DRIC Bridge will be public owned.

According to the literature, most toll price regime studies are theoretical and/or analytical in nature. In this type of studies, road users are typically modeled using a deterministic or stochastic user equilibrium model, while road owners are assumed to engage in toll competition or toll-capacity competition (e.g. Mun and Nakagawa, 2009; van den Berg and Verhoef , 2012; Tan, 2012). A recent summary of theoretical toll road competition studies can be found in van den Berg and Verhoef (2012). A few studies are more relevant to the Windsor-Detroit cross-border setup because they considered multiple governments or countries, or they considered multiple collaboration and/or competition regimes.

For instance, De Borger et al (2007) studied pricing regimes in the case of two transport links, each owned by a different government. In the study conducted by Mun and Nakagawa (2009), a simple two-country model of international trade was built where the transportation cost of the border-crossing depended on the road capacity and toll. Five different alternative pricing regimes were assessed without the consideration of congestion. In the recent study of Tan (2012), the problem of how to set the toll and capacity levels of a new road added onto an existing network with a single link was considered in detail. Likewise, Mun and Nakagawa (2009), tested various ownership regimes (free, public or private owned toll road) of an existing network.

The analysis of traffic flows and toll prices for border crossing transportation facilities characterizes a bi-level equilibrium problem. In this problem, traffic flow reaches a steady state condition where no traveler can achieve any reduction in travel time by unilaterally changing their current assigned crossing. At the same time, tolls on the available crossings will reach a steady state where the owner of a privately owned crossing facilities (e.g. Ambassador Bridge) will not be able to achieve any additional profit by decreasing the tolls when competing with the other facility (e.g. DRIC Bridge). The steady state (i.e. equilibrium) in the bi-level equilibrium problem is reached simultaneously. Existing studies usually converted the bi-level equilibrium problem into a single level problem. For instance, in the study performed by Chen (1999), the toll design problem is converted into a single level optimization problem with certain simplifying assumption.

Despite the current efforts, studies that apply the toll regime modeling framework to real world network are lacking in the literature. Therefore, this thesis fills this existing gap by developing a simulation framework to estimate and forecast the impacts of collaboration and competition regimes for the Windsor-Detroit area in the presence of the DRIC Bridge. Such framework could provide useful suggestions to help transportation planners and decision makers understand the impacts of having a new publicly owned surface crossing (i.e. DRIC Bridge) in one of the busiest border crossing regions in the world.

1.2 The Research Objectives

The aim of this research is to develop and implement a numerical modeling framework for two international bridges to investigate various cross-border toll competition regimes. The specific objectives are:

1) Develop an operational modeling framework for cross-border toll road competitions with an application to the Windsor-Detroit international crossing;
2) Apply the modeling framework to Ambassador Bridge and new DRIC Bridge to explore the outcomes of various toll price regimes.

1.3 Thesis Outline

To successfully explore the impacts of different price regimes on the cross-border network, some empirical conclusions from previous studies are adopted in this research. In order to solve the bi-level toll competition problem for the two bridges, the mesh method (a heuristic algorithm) is used. The approach is used to simulate cross-border traffic flow and associated toll prices for the year 2031.

The rest of thesis is organized as follows. Chapter 2 reviews relevant past studies; Chapter 3 introduces the study area, data and simulation platform, it also presents and discusses the competition model adopted in this research; Chapter 4 explains the rationale for deriving the values of the parameters adopted in the numerical experiments. It also discusses the results from the performed simulations. Finally, conclusions based on the obtained results and directions for future research are given in Chapter 5.

CHAPTER II

LITERATURE REVIEW

The past few decades witnessed a significant growth in travel demand. Changes in lifestyle and globalization have amplified the levels of trade and economic activities between various countries. Consequently, large volumes of goods are shipped across international boundaries every day. A number of theoretical and experimental studies have been conducted in the past to study transportation systems and the flow of traffic across international borders. This chapter provides a review of these studies to set the basis for the research that will be presented in this thesis.

This chapter is organized as follows. Section 2.1 provides a review of studies about toll road competition. Next, section 2.3 gives a review of the literature on traffic equilibrium problems. Section 2.4 sheds light on previous researches for value of time research while section 2.5 discusses the main methods used in past studies to perform traffic analysis and simulation. The last section gives a summary of this chapter and lists the limitation of the previous studies as well.

2.1 Toll Road Competition

Within a road network, competition exists extensively among parallel routes. Based on empirical research, there could be several factors affecting road competition. For instance, toll price and road capacity are significant factors that have been identified in past research. Also, government policies to manage congestion, or to obtain funds and gain profit have been reported (Glaister and Graham, 2004). However, according to Wei et al. (2011), road toll price is the most significant factor that has a direct impact on the traffic assignment when modeling the different available routes.

One central issue regarding toll roads is how the profit-oriented behaviors of toll roads may deviate from the socially optimal outcome, and what kind of government regulation should be adopted to avoid too much welfare loss. Several researchers studied this issue without considering capacity choice, i.e. road capacity is given exogenously. Viton (1995) assessed the economic viability of private roads for the situation where a private toll road competes with a free-access road. He concluded that the private roads can be highly profitable under a range of assumptions about the mix of vehicle types and the costs of travel time, and presented a discussion of regulatory approaches to modify the impacts of simple profit-maximization. Mills (1995) discussed the possibility of divergence between profit and welfare for a tolled link in a simple road network. In particular, he showed that a link that is profitable can nevertheless entail a welfare decrement. Verhoef (1996) and Verhoef et al. (1996) considered a network with one origin and one destination connected by two parallel routes. They examined two private ownership regimes: a regime in which one route is private and the other is free access, and a second regime in which one private firm controls both routes. Braid (1996) made a detailed investigation of a private toll road treating endogenously all three travel decisions: whether to drive, and if so when and by what route, using Vickrey's bottleneck model of queuing congestion (Vickrey, 1969). De Palma and Lindsey (2002) investigated whether private toll road operators will implement time-based congestion pricing in a competitive environment. Three types of competing routes were considered using Vickrey's bottleneck model: private roads, public roads, and free access roads. Verhoef and Small (2004) examined the revenue-maximizing, first-best and second-best pricing schemes under user heterogeneity and elastic demand in a simple network with both parallel and serial links. They showed that product differentiation mitigates the difference between the revenue-maximizing and the first-best results, and that user heterogeneity has more impact on the effectiveness of the second-best policies.

There are also numerical and theoretical studies on toll roads that take road capacity as a decision variable. Yang and Meng (2000) investigated the profitability and social welfare gain of a single new toll road in a general network through numerical experiments. Yang et al. (2002) further examined the impact of user heterogeneity on the profitability and social welfare gain of new toll roads. Without considering the concession period, Ubbels and Verhoef (2004) and Verhoef (2005) analyzed capacity choice and toll setting by private investors in a competitive bidding framework organized by the government. They considered concessionaire selection based on the various criteria of maximization of capacity or patronage, minimization of tolls or minimization of toll revenues, and compared the resulting welfare gains (or losses) from each criterion. De Borger and Van Dender (2005) analyzed a model with two substitute congestible facilities under three administrative regimes: (a) social optimum, (b) monopoly, and (c) duopoly in a sequential capacity-then-toll game. They showed that equilibrium time delays are equal in regimes (a) and (b), but higher in regime (c). Namely, pricing and capacity choices under monopoly do result in the socially optimal service quality. This result was derived theoretically by assuming a linear inverse demand function. Xiao et al. (2007a) obtained a more general result when studying the inefficiency of the oligopolistic equilibria of toll road competition. They proved that at both oligopolistic equilibria and social optimum, the volume/capacity ratio of each road remains unchanged and is only determined by the road's own unit construction cost. Wu et al. (2011) extended their results to general networks. Xiao and Yang (2008) analyzed a network consisting of a congested tolled highway competing with an uncongested untolled substitute, adopting a continuous VOT distribution among a fixed travel demand. They examined the deviation of the private firm's choice from the socially optimum solution under different government regulations. In the recent study of Tan (2012), the problem of how to set the toll and capacity levels of a new road added onto an existing network with a single link was considered in detail. In this study, the government is assumed to concern only the network efficiency, and based on that it is reported that the government selects the toll and capacity levels is equate to that of the first-best scenario (both roads are public toll roads) under all ownership regimes.

Another research subject regarding toll roads is the market of private toll roads, in particular the competition among private roads. Several researchers (some already mentioned) have studied toll competition among private roads for the case of simple networks with parallel links (De Vany and Saving, 1980; De Palma, 1992; De Palma and Lindsey, 2002). In a general network context, Yang and Woo (2000) studied toll road competition using a game-theoretic approach. Wang et al. (2004) examined the strategic interactions and market equilibria of a bilateral monopoly (a private road operator and a private bus service provider) on a private highway. There are also several papers focused on the inefficiency bound (similar to the term “price of anarchy”) of toll road competition (Engel et al., 2005; Acemoglu and Ozdaglar, 2005; Hayrapetyan et al., 2005; Xiao et al., 2007a; Xiao et al. 2007b). Van den Berg and Verhoef (2012) provided a summary of private toll road competition studies. They also considered the Nash competitions and Stackelberg competitions where capacity and toll setting are separate stages.

A few studies considered multiple governments or countries, which is directly relevant to our cross-border setup. De Borger et al (2007) performed their study focusing on pricing regime in a congested transport corridor with two parallel links between two countries, and each of the links is controlled by a different government. It is found that capacities are strategic factors for the links of different regions, and higher capacity investment of a given country not only reduces optimal tolls within its own region but it also raises the transit tolls on the other link. As a complement of the research just mentioned, Mun and Nakagawa (2009) developed a simple two-country model of international trade. Five different pricing regimes were assessed without congestion and only trips between neighboring countries were considered. It is found that the break-even pricing regime could gain higher warfare than the free access regime. They also found that some different regimes yield the same result, for instance, government pricing regime and profit maximization regime, break-even pricing regime and user cost minimization regime, etc. A recent review of the literature on pricing and investment decisions with competing governments is given by De Borger and Proost (2012).

2.2 Traffic Equilibrium Model

When a new link is added to the existing cross-border transportation network, a new pattern of traffic will likely emerge. Based on previous studies, toll pricing problems are usually based on different assumption of traffic equilibrium. The latter refers to a stable condition of traffic flow pattern that characterizes the interaction between travel decisions (i.e. demand) and performance of the transportation network (i.e. delays).

Typically, traffic equilibrium models have been used to predict the steady state traffic flow patterns in transportation networks subject to congestion. Traditionally, two traffic equilibrium models have been developed and used: the deterministic user equilibrium (UE) model and the stochastic user equilibrium (SUE) model (Chen, 1999). The concept of traffic equilibrium is pioneered by Knight in 1924. According to Sheffi (1985), both UE and SUE are well defined traffic assignment methods. UE is defined as reaching "a stable condition when no traveler can improve his travel time by unilaterally changing routes". Here, travelers are assumed to be identical in terms of their route choice behavior. Different from the UE, travelers in SUE have different perception of travel time on the available routes connecting their origin to their destination.

2.2.1 User Equilibrium Problems

To decipher the network design problem more precisely, the algorithms for UE problems will be demonstrated first in this section following the presentation given in Sheffi (1985).

Note that the representation of the network defined in the following paragraph will also be adopted in the section discussing the SUE problem.

Through the network, each O-D pair r-s is connected by a set of paths. Let R denote the origin centroids set. Also, let S denote the destination centroids set, while let K_{rs} represent the set of paths, where r ∈ R and s ∈ S. For each path k, f_k^{rs} is used to represent the flow. Let x_a and t_a denote the flow and travel time on each link. Total travel demand q is fixed, which can be estimated based on the zonal growth data in population and employment. Under the UE situation, the results of the equilibrium assignment problem can be obtained by solve the following optimization model:

$$\min z(v) = \sum_a \int_0^{x_a} t_a(\omega) d\omega \qquad (2.1)$$

subject to

$$\sum_k f_k^{rs} = q^{rs} \qquad \forall\, r, s \qquad (2.2)$$

$$f_k^{rs} \geq 0 \qquad \forall\, k, r, s \qquad (2.3)$$

and definitional constraints

$$x_a = \sum_r \sum_s \sum_k f_k^{rs} \delta_{a,k}^{rs} \qquad \forall\, a \qquad (2.4)$$

Note that the travel time factor $t_a(\omega)$ on link a in equation 2.1 is a function of flow ω. The above equation means that in the network, the flow on each link equals the total flow on all the paths passing the link. The indicator variable $\delta_{a,k}^{rs}$'s value equals 1 if link a is included in path connecting O-D pair r-s, and equals 0 otherwise. β is utilized to convert toll to travel time.

To date, many efforts have been made to develop toll-competition based models where the UE is utilized. Verhoef et al. (1996) performed their study with a two-link network simulation model under a static UE condition. In a later study, Yang and Woo (2000) investigated the competitive Nash equilibrium graphically by considering two private operating toll roads. In the exploratory research conducted by Bar-Gera and Boyce (2005), the characteristics of route sets in the solution to an integrated user equilibrium model is illustrated clearly. Recently, Tan (2012) investigated the problem of toll and capacity level setting of an add-on road using the UE model.

2.2.2 Stochastic User Equilibrium Problems

In SUE network design problems, equilibrium will be reached when no traveler believes that his/her travel time can be shorter on any other route than the one currently used. Within a network, the following stochastic user equilibrium (SUE) condition always holds:

$$f_k^{rs} = q^{rs} P_k^{rs} \ \forall\, k, r, s \tag{2.5}$$

where $P_k^{rs}$is the probability that route k within the network has been chosen based on measured perceived travel times. Additionally, the basic constraints should also hold for the network:

$$t_a = t_a\,(x_a) \qquad \forall\, a\,, a \in A \tag{2.6}$$

$$\sum_k f_k^{rs} = q^{rs} \qquad \forall\, r, s \tag{2.7}$$

where $x_a$is the trip rate on link a within the consecutive link set A, and

$$x_a = \sum_r \sum_s \sum_k f_k^{rs} \delta_{a,k}^{rs} \tag{2.8}$$

The indicator variable $\delta_{a,k}^{rs}$'s value equals 1 if link a is included in path connecting O-D pair *r*-*s*, and equals 0 otherwise.

Compared with the UE model, the SUE model has been shown to produce more realistic results yet its application in empirical toll price studies is more complicated given its probabilistic nature. Bergomi (2009) applied the concept of SUE for estimating the equilibrium travel times and flow pattern. In this study, the SUE case is proved to require more computational work than the deterministic UE, since a large number of potential routes have to be considered simultaneously. Recently, Liu et al. (2013) presented a study to formulate a practical speed-based toll design problem by applying a mathematical programming problem with a probit-based stochastic user equilibrium model. Chen (1999) used both UE and SUE methods in toll design problems, and demonstrated that the relationship between the two methods is very tight. In essence, the UE problem is a special condition of the SUE problem. However, UE modeling was more feasible since the number of equilibrium constraints in the case of the SUE was proved to be rather large for a real-sized network and consequently heavy computational work would be required.

2.2.3 Two-Link Network to Illustrate Toll Road Competition

To illustrate the toll competition theory and bi-level modeling problem more clearly, a simple two-link example will be demonstrated first here.

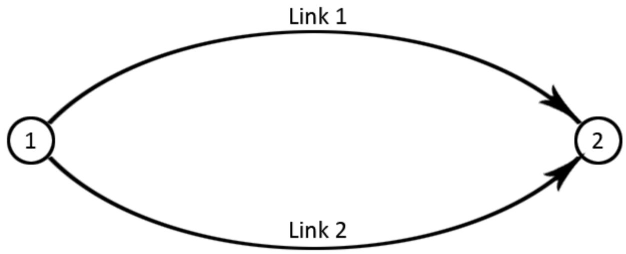

Fig. 2.1 A two-link network

Consider two links connecting one origin-destination (OD) pair as depicted in figure 2.1. These two links represent two different paths, leading from the origin, node 1, to the destination, node 2. The travel time functions for the two links are:

$t_1(v_1) = t_0 + v_1$

$t_2(v_2) = t_0 + v_2$

where $t_0$he free flow travel time of both is links, v_1 and v_2 are the traffic volumes on the two links, respectively.

Total travel demand (or total traffic volume) between this OD pair is d, given and fixed.

$$v_1 + v_2 = d$$

Each link is assumed to be a private toll road operated by a private firm, and each firm would like to set a toll level which can maximize its own revenue. Assuming user equilibrium traffic assignment; the total cost of each link to road users is travel time plus toll. For ease of exposition, consider the unit of toll is already converted to time unit by a VOT parameter, and thereby the total costs of the two links can be written as

Link 1: $\tau_1 + t_1(v_1)$

Link 2: $\tau_2 + t_2(v_2)$

where $\tau_1$and τ_2 are the toll prices set by Firm 1 and Firm 2, respectively.

To determine the equilibrium tolls charged on the two links, a bi-level model could be applied here. In the following part, two situations of the two-link example will be discussed: without pavement cost and with pavement cost.

Two-link problem without pavement cost

In this case, pavement cost will not be a concern when we solve the competition problem. Based on the above considerations, both of the two private firms aim at maximizing the revenue, which can be expressed as

$$\begin{cases} Link\ 1:\ \tau_1 = \arg\max \tau_1 v_1(\tau_1, \tau_2) \\ Link\ 2:\ \tau_2 = \arg\max \tau_2 v_2\ (\tau_1, \tau_2) \end{cases}$$

where the equilibrium flows $v_1$and v_2 can be calculated by solving the following lower-level user equilibrium problem:

$$\min z(v) = \int_0^{v_1}(t_0 + \omega)d\omega + \tau_1 v_1 + \int_0^{v_2}(t_0 + \omega)d\omega + \tau_2 v_2 \frac{\tau_2 - \tau_1 + d}{2} \qquad (2.9)$$

subject to

$$v_1 + v_2 = d \tag{2.10}$$

$$v_1, v_2 \geq 0 \tag{2.11}$$

To simplify the above equilibrium problem for this two-link problem, the original formulation can be written as:

$$\min z(v) = \int_0^{v_1} (t_0 + \omega) d\omega + \tau_1 v_1 + \int_0^{d-v_1} (t_0 + \omega) d\omega + \tau_2 (d - v_1)$$

subject to

$$v_1, d - v_1 \geq 0$$

By solving the above one-variable minimization problem, v_1 and v_2 can be obtained:

$$v_1 = \frac{\tau_2 - \tau_1 + d}{2} \tag{2.12}$$

$$v_2 = \frac{\tau_1 - \tau_2 + d}{2} \tag{2.13}$$

It should be mentioned that the above solution (2.12) and (2.13) can also be directly solved by using the UE condition $\tau_1 + t_1(v_1) = \tau_2 + t_2(v_2)$. Here we used the UE problem formulation just to highlight the bi-level nature of the problem.

Substituting expressions (2.12) and (2.13) into the upper-level maximization problems, the objective functions become:

Firm 1: $\max\ \tau_1 v_1(\tau_1, \tau_2) = \tau_1 * \frac{\tau_2 - \tau_1 + d}{2}$ (2.14)

Firm 2: $\max\ \tau_2 v_2(\tau_1, \tau_2) = \tau_2 * \frac{\tau_1 - \tau_2 + d}{2}$ (2.15)

The solution of the above mathematical program is:

$$\begin{cases} Link\ 1: \tau_1(\tau_2) = \frac{\tau_2 + d}{2} \\ Link\ 2: \tau_2(\tau_1) = \frac{\tau_1 + d}{2} \end{cases} \tag{2.16}$$

Expression (2.16) gives the best-response curve of each firm given the other firm's toll level, which is plotted as below:

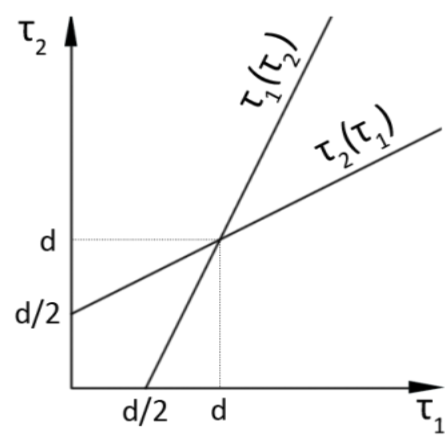

Fig. 2.2 Toll competition functions between the two links under UE

The above figure reveals the toll competition pattern between the two firms. If the toll of Firm 1 is fixed to 0, the revenue-maximizing toll of Firm 2 will be $\tau_2 = d/2$, and vice versa. However, the toll competition equilibrium solution can only be obtained when the tolls can satisfy the maximization problems (2.14) and (2.15) simultaneously. As marked in the figure, when both of the firms set their tolls to d, the revenue maximization point under user equilibrium can be reached for both firms. That is to say, the equilibrium toll charged on each links is *d* in this example.

Two-link problem with pavement cost

Let *m* denote the pavement cost for each truck on the two bridges. In this situation, the pavement costs should be subtracted before estimating the profits. Considering the pavement cost m, the problem can be solved as

$$\begin{cases} Link\ 1\text{: } \tau_1 = \arg\max(\tau_1 - m)v_1(\tau_1, \tau_2) \\ Link\ 2\text{: } \tau_2 = \arg\max(\tau_2 - m)v_2(\tau_1, \tau_2) \end{cases}$$

where the equilibrium flows $v_1$and v_2 can be calculated by solving the lower-level user equilibrium problem shown in (2.9) to (2.11) .

Using the UE condition $\tau_1 + t_1(v_1) = \tau_2 + t_2(v_2)$, v_1 and v_2 here can be solved as shown in (2.12) and (2.13).

For the upper-level problem, the objective functions for the two firms become:

Firm 1: $$\max\ (\tau_1 - m)v_1(\tau_1, \tau_2) = (\tau_1 - m) * \frac{\tau_2 - \tau_1 + d}{2} \quad (2.17)$$

Firm 2: $$\max\ (\tau_2 - \mathrm{m})\mathrm{v}_2(\tau_1, \tau_2) = (\tau_2 - m) * \frac{\tau_1 - \tau_2 + \mathrm{d}}{2} \quad (2.18)$$

In this context, τ_1 and τ_2 can be solved as

$$\begin{cases} Link\ 1: \tau_1(\tau_2) = \frac{\tau_2+d+m}{2} \\ Link\ 2: \tau_2(\tau_1) = \frac{\tau_1+d+m}{2} \end{cases} \tag{2.19}$$

And the equilibrium tolls can also be solved as:

$$\begin{cases} \tau_1 = d + m \\ \tau_2 = d + m \end{cases} \tag{2.20}$$

From the above equations, it can be seen that the equilibrium toll is proportional to the pavement cost and the pavement cost is translated to the travelers in the system. Since the total travel demand is fixed, the equilibrium toll prices for the two links will definitely increase with the growth of the pavement cost. However, the total revenue at the equilibrium point of the two firms will keep the same since the pavement cost will be cancelled out during the calculation. This example indicates that within this two-link system, the change of the pavement cost can directly influence the equilibrium toll price, but will not change the total revenue when the problem is linear.

Different from the two-link network examples, in this project, DRIC is operated by government while Ambassador Bridge is privately-owned. The market objective of the Ambassador Bridge is always profit and the DRIC's goal can be either profit or social-welfare. In the competition, operators of DRIC and Ambassador Bridge can decide their own toll prices and the SUE method were adopted.

2.3 Value of Time

In transport economics, the concept of value of time (VOT) stands for the opportunity cost of the time that a commuter spends on the journey. Essentially, travel time plays a vital role in the general cost of any trip. Sufficient empirical findings to estimate VOT can be found in previous studies (e.g. Calfee and Winston, 1998; Lam and Small, 2001; Whelan and Bates, 2001; Lake and Ferreira, 2002; Brownstone and Small, 2003; Holgu ń-Veras and Cetin, 2008; Transport Appraisal and Strategic Modelling (TASM) Division, 2012). The literature indicates that VOT varies widely for travelers with different level of wage, gender, age, trip purpose, length of the trip, and so on. However, since travel time is a significant component of a commuter's travel cost, different VOT time and travel time savings could give rise to different attractive ability for every transport project (Button, 2004).

Lake and Ferreira (2002) obtain some useful conclusions about the rates of VOT based on personal income. They found that for non-business trips, 40% to 50% of average income rates is widely accepted, while rates of up to 80% to 100% of the income rate is adopted for business trip. Therefore, with certain empirical converting rates, the value of time of an area could be generated according to the average local income. Based on certain assessment, the average VOT for vehicle travel can be estimated to range from $7.50 to $10.00 per hour using the mean hourly income of $15.01 and $20.08 for non-metropolitan and metropolitan areas, respectively (US Bureau of Labor Statistics, 2007). Nevertheless, in some particular circumstances, making a simple assumption of a uniformed value of time for all commuters within a network has been reported. Zhang and Levinson (2006) assumed a uniform VOT of 10 dollars per hour for all travelers.

2.4 Traffic Analysis Methods

The urban transport modeling system (UTMS) has been used since the 1950s to simulate traffic flows on the transportation network. In most cases, the UTMS makes use of the UE method to simulate network traffic flows (Kuzmyak, 2008). Figure 2.3 illustrates the general structure of the UTMS simulation method.

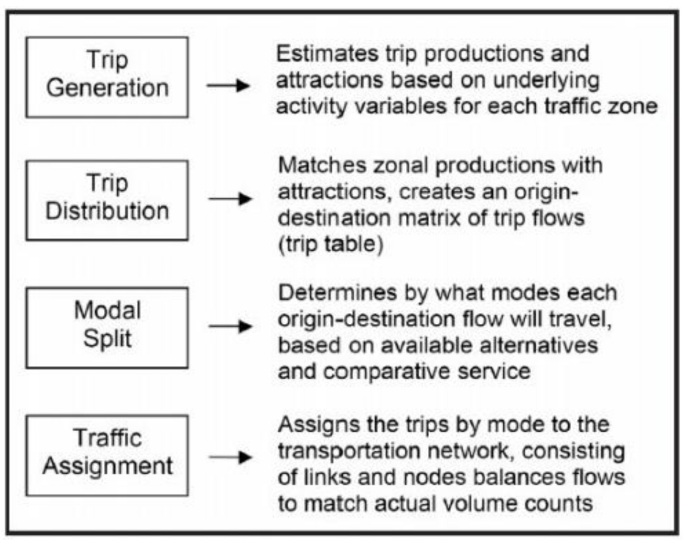

Fig. 2.3 Four-step transportation planning model structure

(Source: NCHRP Synthesis 384, Forecasting metropolitan Commercial and Freight Travel, 2008)

UTMS, also known as the four-stage model, is often utilized for trip estimation (i.e. travel demand) during the first 3 stages (as in figure 2.3) and then the UE traffic assignment is applied as the 4th stage. Typically, the urban area is divided into a set of mutually exclusive and collectively exhaustive set of traffic analysis zones (TAZs). Land use activity information (e.g. population and employment) per TAZ are then collected and projected for future years. Data from household travel surveys and commercial travel surveys are used to estimate the parameters of the different components of the UTMS.

In the trip generation stage, regression models are normally estimated and used to predict the trip productions O_i and attractions D_j per TAZ. Typically, O_i and D_j are modeled as a linear function of land use activities variables such as population and employment. In the trip distribution stage, a gravity model is usually estimated and then used to predict the trip matrix **T** summarizing the number of trips T_{ij} between any two pairs of TAZs *i* and *j*. The gravity model makes use of the predicted O_i's and D_j's from stage 1 when estimating matrix **T**. Next, The modal split stage relies on discrete choice models (e.g. Multinomial Logit or Nested Logit model) to split the trip matrix **T** produced in stage 2 by travel mode. The result is a set of matrices $\mathbf{T}^{\mathbf{m}}$ that summarize the number of trips "by a given mode **m** (e.g. motorized mode)" between any two pairs of TAZs *i* and *j*. Finally, the 4th stage is executed to assign the motorized trip matrix $\mathbf{T}^{\mathbf{m}}$ (m = motorized) to the road network via the UE or SUE model. Although the four-stage model has not been used in the past to estimate cross-border traffic, the method could be extended to do so.

2.5 Summary

This chapter reviews the relevant past studies from various aspects. The importance of the Windsor-Detroit border was first emphasised. Based on the statistical data presented in section 1, it can be seen that the Ambassador Bridge is the most critical crossing in the study area and the cross-border truck flow could be boost through certain effective measures. The new DRIC Bridge is expected to play the important role in facilitating the movement of people and goods through the Windsor-Detroit trade corridor and promoting the bilateral economy.

To ensure the accuracy and validity of the simulation results, proper equilibrium situation is quite important. From the discussion of the two different kinds of equilibrium problems, the SUE is proved to be more feasible for the modeling framework in this study.

It is also necessary to take into account that which analysis methods should be used to investigate the impacts of different traffic regimes. UTMS can be used for trip assignment during the simulation progress. The sensitivity analysis is able to help us revealing the pattern of the traffic situation of the study area.

Thanks to previous studies, many useful findings could be used in this project. However, there also have some limitations of these studies. As mentioned before, analysis for toll price regime modeling has been conducted from a theoretical perspective in most cases. Therefore, studies which apply the toll regime modeling to a real world network are lacking and required. It is important to develop and implement a modeling framework for toll road competitions under various regimes for the Windsor-Detroit area. By applying the modeling framework to the real-sized network of Windsor-Detroit border crossing area, the impacts brought by different toll price regime could be thoroughly investigated in this research.

CHAPTER III
DATA & METHODOLOGY

3.1 Study Area & Research Data

3.1.1 Study Area

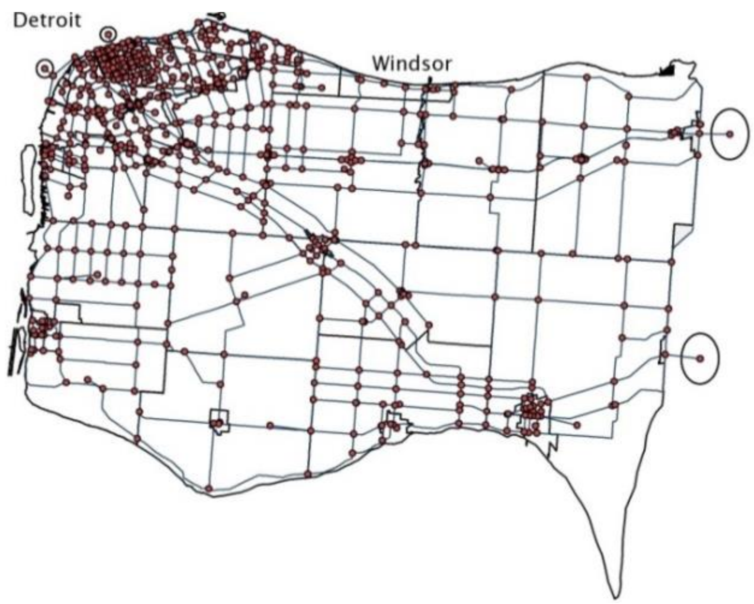

Fig. 3.1 Map of study areas

The study area in this research is confined to the Windsor-Essex region and the border crossings connecting Windsor to Detroit, Michigan. The map displaying the study areas is shown in figure 3.1. The whole study area is divided into 83 traffic analysis zones (TAZ) with their own geographic codes. The Canadian Census was used to obtain population and employment figures for the different zones. Such data are used to predict trip productions and attractions from/to each TAZ. The road network, as shown in figure

3.1, consists of 1226 links and 791 nodes. Traffic flow on each link can also be estimated based on various factors such as travel time, capacity and/or toll prices. These factors are important since, travelers are more likely to choose a shorter or less congested path or one with lower toll. At the same time, paths with higher cost (in terms of travel time or toll) are usually expected to be less attractive when travelers are making their route choices.

The Windsor-Detroit Border Crossing is the most critical among all the crossings along the Canada-US border. This border handles a significant percentage of the daily bilateral trades between the two countries (Anderson, 2012). As an important gateway for Canada's trade, the Windsor-Essex County stands as the southernmost part of Canada to the south of Detroit, Michigan in the United States, within the Province of Ontario. The county's current population is estimated at 388,782 including the population of Windsor, with a density of 210.1/km^2 (Statistics Canada, 2012). According to a recent report by Wilbur Smith (2010), the Windsor region is expected to grow in terms of its population and employment. The same could be said about Ontario (Statistics Canada, 2012). However, the growth rate for Detroit and the state of Michigan is projected to have negative growth in the future.

Trade between Canada and the United States experienced a significant growth from 1994 to 2009, with an increase rate of 245% (U.S. Bureau of Transportation Statistics, 2009), as a result of the free trade agreements that were signed between the two countries. Although bilateral trade decreased after the economic downturn in 2009, Canada is still ranked as the leading exporter and importer to/from the United States (Wilbur Smith, 2010). According to Statistics Canada (2011), during the year of 2010, the bilateral trade volume was more than $600 billion, with at least $1.7 billion worth of merchandise and services passing through the border every day. As the most critical of all Canadian border crossings, the Windsor-Detroit crossing carries about one third of all Canada-United States trade in terms of shipped goods (Statistics Canada, 2011).

Anderson (2012) noted that there is a strong connection between Ontario's economy and its cross-border transportation links with the United States. The trade structure between Ontario and the United States has been investigated and many interesting results were obtained. For instance, 87% of all exported merchandise pertain to manufactured goods. As a result of this type of freight movement structure, higher requirements are imposed on the transport costs and travel time for crossing the border. As for transportation mode, trucks are the most widely used mode for Ontario's exports to the United States (Anderson 2012).

To date, there are three crossings that connect Ontario and Michigan: the Ambassador Bridge, the Detroit–Windsor Tunnel and the Blue Water Bridge. However, when it comes to freight traded by trucks, the Ambassador Bridge stands as the most critical connecting point. Earlier studies suggest that the three border crossings handled more than 11.2 million passenger vehicles and 3.7 million commercial vehicles annually, thus accounting for more than half of all the commercial flows between the two countries (Wilbur Smith 2010).

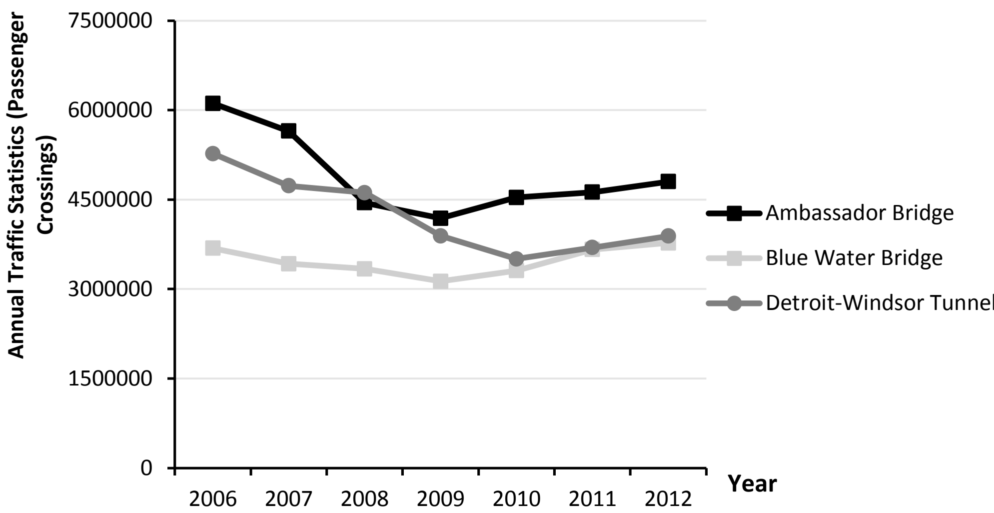

Fig. 3.2 Annual traffic statistics of passenger crossings (Source: PBOA, 2013)

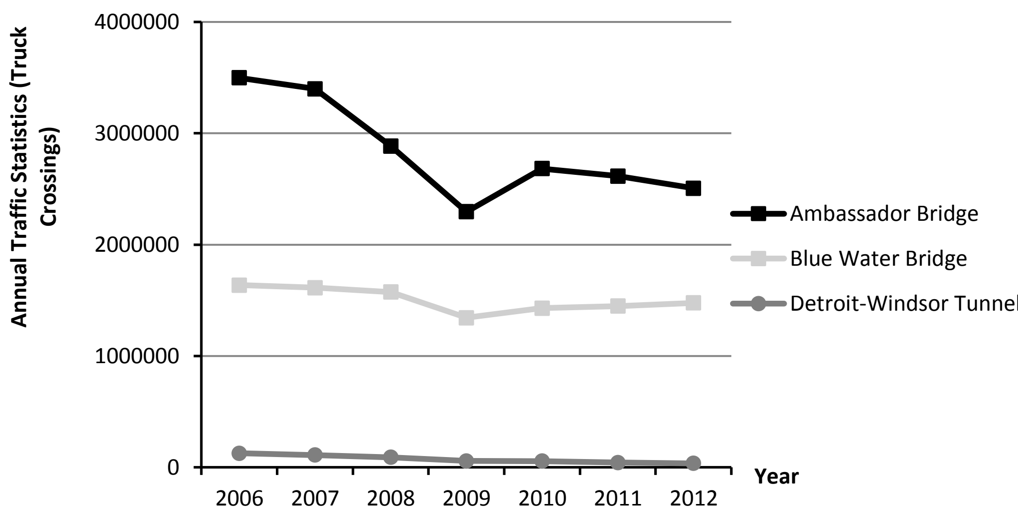

Fig. 3.3 Annual traffic statistics of truck crossings (Source: PBOA, 2013)

Figures 3.2 and 3.3 are plotted based on statistical data published by Public Border Operators Association (PBOA, 2013). Figure 3.2 shows that after the economic downturn in 2009, there is a general growing trend in border crossing for passenger vehicle trips. The data also indicates that almost 40 percent of all the passenger crossings are handled by the Ambassador Bridge.

Accordion to figure 3.3, after a significant growth from 2009 to 2010, the volume of trucks crossing the border experienced a slow decrease in the following two years. This situation could be due to the slow economic recovery and the lack of cross-border cooperation between local authorities on both sides of the border. As shown in the figure, the Ambassador Bridge retains the lion's share of truck trips with over 60 percent of truck crossings.

According to Sheffi (1985), travel time and travel costs can directly affect drivers' decisions within the transportation system. To obtain a general border crossing cost on each bridge, travel time and toll price of vehicles are usually used during the analysis. Anderson (2012) reported that the average crossing time on the Ambassador Bridge is 11.3 minutes from 2008 to 2009. Historical data on toll prices for the Ambassador Bridge can be found in the literature. In 1957, the toll price on this bridge was 60 cents per vehicle plus 10 cents for each passenger. Since then, the toll price level has experienced several increases with the times. Recently, the passenger toll price on Ambassador Bridge was increased from $4.75 to $5.00, ranking as the highest among all the Canada-US border crossings. In the study conducted by Wilbur Smith (2010), it is reported that the annual growth rate of passenger toll was 5.5% from 2002 to 2009. With regards to the toll setting for commercial vehicles, the current toll rates given by the Ambassador Bridge are $3.50/axle for Class A trucks, $4.00/axle for Class B trucks and $5.50/axle for Class C trucks. Compared to the toll price for trucks in 2009, as reported by Wilbur Smith (2010), the toll prices increased $0.75/axle for each truck class.

The New Bridge

Fig. 3.4 Projection of DRIC Bridge

(Source: New International Trade Crossing, http://buildthedricnow.com)

Linked by the automobile industry, significant cross-border labor and recreational opportunities, the Windsor-Detroit crossing region is portrayed as an area with high level of institutional integration and intermunicipal coordination. In order to enhance the bilateral economic growth and long-term prosperity, the Detroit River International Crossing (DRIC), as shown in figure 3.4, is proposed to be built as a new border crossing over the Detroit River next to the Ambassador Bridge.

The DRIC Bridge, which now is named as the New International Trade Crossing (NITC), will link the new Herb Gray Parkway in Windsor with I75 and I94 in Detroit. With the improvements brought by the new bridge, enhanced flows of people and goods across the border could boost the development of job opportunities, health care, education, recreation and tourism on both sides of the border (Nelles, 2011).

3.1.2 Data sets

The following data were used to perform the analysis in this study:

1. Current transportation policy of the cross-border area
2. Official forecast documents that relate to the anticipated future growth in the city;
3. Population, economic, transportation and other geographic data of the city;
4. Road network data of the city;
5. Current data on trade through the crossing;
6. Current land use data of the city.

Based on official projections, region-wide growth in population and employment has been estimated for the period 2006-2031. The allocation of this growth across the different traffic analysis zones was based on the work reported in Gingerich et al. (2014). PM Peak Hour (4 PM) trip productions and attractions for each zone were estimated to create future demand Origin-Destination matrices for passenger vehicles (PV) as well as light (LV), medium (MV) and heavy (HV) commercial vehicles.

3.1.3 Main assumptions

Since multiple classes of vehicles and a real traffic network are considered in this study, we introduced few assumptions, as shown below, to make the modeling work feasible.

Restricted Passenger Toll

Due to political constraint, we assume that both bridges will set their passenger car tolls at the highest politically-acceptable level. As such, the passenger car tolls of the two bridges are the same and exogenously given. This assumption is reasonable given that the Ambassador Bridge and the Detroit-Windsor Tunnel charge the same passenger car toll most of the time. With this assumption, each bridge's strategy reduces to its truck toll level, and the competition equilibrium (i.e. Nash equilibrium) emerges when each bridge cannot improve its objective function by unilaterally changing its truck toll level.

Fixed Travel Demand

Since the competition problem in this research involves multi vehicle classes and a real traffic network, dealing with variable travel demand can complicate the toll competition problem. Therefore, the total travel demand q is assumed to be fixed for the border crossing area. Such assumption assumes that international trade is mainly determined by the economy but not by the border crossing toll. On the other hand, fixed travel demand for passenger cars is a reasonable assumption since we are modeling flows during the PM peak hour.

Duopoly Price Game

The price competition we considered in this study is focused on the Ambassador Bridge and the new bridge. Although the Detroit–Windsor Tunnel and the Blue Water Bridge are also responsible for part of the border crossing traffic, the majority of the flows across the border will use the Ambassador Bridge and the new bridge.

3.2 Competition Regimes

In order to address the toll competition problem in this study, a bi-level equilibrium modeling framework was adopted to formulate and solve the toll competition problem. Generally, the upper level of the bi-level modeling framework is known as the operator level while the lower level is known as the traveler level. Depending on different ownership and purpose, the objective of the operators could be different. Suppose the operator of the Ambassador Bridge is always bent on profit, and the DRIC's operator has diverse competitive strategies based on different objectives.

Let A be the set of consecutively numbered links forming the road network; N be the set of consecutively numbered nodes; and let v_a and t_a denote the flow and travel time on link a ∈ A. Through the network, each O-D pair r-s is connected by a set of paths. If R denote the origin centroids set and S denote the destination centroids set, then we can define K_{rs} as the set of paths connecting r to s, , where r ∈ R and s ∈ S. For each path k, f_k^{rs} is used to represent the flow. The value of time β in this project will be used for the reciprocal conversion between travel time and toll. Here, total travel demand q is fixed, which can be estimated based on the zonal growth in population and employment of the study area from the period 2006 to 2031. Within the border crossing network, the following stochastic user equilibrium (SUE) condition always holds:

$$f_k^{rs} = q^{rs} P_k^{rs} \ \ \forall\, k, r, s \tag{3.1}$$

where P_k^{rs} is the probability that route k within the network been chosen based on measured perceived travel times.

Additionally, the basic constraints should also hold for the network:

$$t_a = t_a(x_a) \qquad \forall\, a, a \in A \tag{3.2}$$

$$\sum_k f_k^{rs} = q^{rs} \qquad \forall\, r, s \tag{3.3}$$

where x_a is the trip rate on a link within the consecutive link set A, and

$$x_a = \sum_r \sum_s \sum_k f_k^{rs} \delta_{a,k}^{rs} \tag{3.4}$$

The indicator variable $\delta_{a,k}^{rs}$'s value equals 1 if link a is included in path k, and equals 0 otherwise.

Using the COMMUTE software, a multi-class traffic assignment which simulates simultaneous traffic flow for passenger vehicles and commercial vehicles under SUE is performed in this study. In the following, five different price regime scenarios will be discussed.

3.2.1 Regime 1

In this regime, both operators of the Ambassador Bridge and the DRIC Bridge choose to maximize their profits by selecting their toll charge. Let v_1 and v_2 represent the traffic volume on the Ambassador Bridge and the DRIC Bridge. Denote t_1 and t_2 as the travel time of the Ambassador Bridge and the DRIC, and let τ_1 and τ_2 be the toll prices on the two bridges, respectively. In this study, β is utilized to convert travel time to toll. The general travel cost C for each bridge can be represented as follows:

$$C = \tau + \beta t + \alpha \tag{3.5}$$

Since the aims of the operators in this regime are to maximize the profits, the problem to be solved can be expressed as follows:

$$\begin{cases} Ambassador\ Bridge: \max(\tau_{1P}v_{1P} + (\tau_{1H} - M)v_{1H}) \\ DRIC\ Bridge: \qquad \max(\tau_{2P}v_{2P} + (\tau_{2H} - M)v_{2H}) \end{cases} \tag{3.6}$$

where the letters P and H in the above subscripts refer the corresponding parameters of passenger vehicle class and the heavy trucks crossing the border. For passenger vehicles, the toll price $\tau_{1P}$and τ_{2P} are given and fixed to a certain level in each regime. Meanwhile, the toll price of heavy vehicles $\tau_{1H}$and τ_{2H} are decision variables in this study. M denotes the maintenance cost caused by each heavy truck, as a function of different factors such as the vehicles' axle weights, travel speeds, etc. In this equation, $v_1$and v_2 are parts of the optimal solution to the aforementioned lower-level SUE problem (3.1)-(3.4).

3.2.2 Regime 2

For the sake of efficiency of the network, the objective of the government should be changed to minimize the total travel cost of the commuters. In light of this purpose, two different situations could be derived to solve the problem: minimize the total travel cost on the two border-crossing bridges and minimize the total travel cost for of the entire network. In regime 2, the operator of the DRIC Bridge cares of the efficiency of the heavy trucks passing the two bridges while the owner of the Ambassador Bridge still chooses to change the toll to maximize his profit.

Using the parameters defined in regime 1, the mix duopoly problem of regime 2 could be expressed as:

$$\begin{cases} Ambassador\ Bridge: & \max(\tau_{1P}v_{1P} + (\tau_{1H} - M)v_{1H}) \\ DRIC\ Bridge: & \min(t_1 v_{1H} + t_2 v_{2H}) \end{cases} \tag{3.7}$$

where v_1 and v_2 are also parts of the optimal solution to the aforementioned lower-level SUE problem (3.1)-(3.6).

In equation (3.7), the optimal function of the Ambassador Bridge is same with the one in regime 1, since the objective of this bridge is supposed to be profit maximization for all of these five regimes. On the other hand, from the optimal function of the DRIC Bridge, it can be seen that the goal is to change the toll of DRIC to minimizing the total travel cost of heavy trucks on the two border-crossing bridges.

3.2.3 Regime 3

Similar with regime 2, regime 3 is also a mix duopoly problem. The only difference is that the travel cost of passenger vehicles is also considered in DRIC's competition strategy. To estimate the total travel cost of multi-class vehicles, the travel costs of these two vehicle groups are converted to equivalent monetary cost using the VOT factor. In this case, the problem to be solved can be expressed as follows:

$$\begin{cases} Ambassador\ Bridge: max(\tau_{1P}v_{1P} + (\tau_{1H} - M)v_{1H}) \\ DRIC\ Bridge: \quad min((t_1 v_{1P} + t_2 v_{2P})\beta_P + (t_1 v_{1H} + t_2 v_{2H})\,\beta_H) \end{cases} \tag{3.8}$$

where $v_1$and v_2 are parts of the optimal solution to the aforementioned lower-level SUE problem (3.1)-(3.4). $\beta_P$and $\beta_H$represents the VOT factor of passenger vehicles and heavy trucks respectively.

From the monetary cost function in the above equation, it can be seen that the DRIC's objective here is to change the toll to minimize the total travel cost of all the vehicles through the two bridges.

3.2.4 Regime 4

As discussed previously, when considering the network efficiency, another alternative for the DRIC's operator is minimizing the total travel cost for of the entire network. In this situation, the problem of the Ambassador Bridge is to maximize its profit as before, and the DRIC is aimed of minimize the heavy trucks' travel cost of the whole network. The optimal problem in this regime is captured as:

$$\begin{cases} Ambassador\ Bridge: \max(\tau_{1P}v_{1P} + (\tau_{1H} - M)v_{1H}) \\ DRIC\ Bridge: \quad \min \sum_{a\in A} t_a v_{aH} \end{cases} \tag{3.9}$$

where t_a represents the travel time on link a, and v_{aH} denotes the corresponding heavy vehicle trip rate. As above, v_1 and v_a are parts of the optimal solution to the aforementioned lower-level SUE problem (3.1)-(3.4).

Compared to the objective functions in regime 2 and regime 3, in this case, the DRIC cares the travel cost of the heavy vehicles throughout the entire network. To fulfill this, the DRIC will choose the toll which gives the minimum results under the SUE condition.

3.2.5 Regime 5

Compared to regime 4, the heavy vehicle class is no longer the only concern of the DRIC Bridge in regime 5. All the vehicles in the study area are taken into consideration to optimize the network efficiency. The optimal problem in this regime can be expressed as:

$$\begin{cases} Ambassador\ Bridge: \max(\tau_{1P}v_{1P} + (\tau_{1H} - M)v_{1H}) \\ DRIC\ Bridge: \qquad \min \sum_{a \in A}(t_a v_{aP} \beta_P + t_a v_{aH}\, \beta_H) \end{cases} \tag{3.10}$$

where t_a represents the travel time on link a, and v_{aP} and v_{aH} represent the corresponding passenger and heavy vehicle trip rate. As above, $v_{aP}$and v_{aH} are parts of the optimal solution to the aforementioned lower-level SUE problem (3.1)-(3.4).

By comparing the above five regimes, we can see that except regime 1, the DRIC Bridge in the other regimes aims at minimizing the travel cost. Regime 2 and regime 3 consider the travel cost on the two bridges, when regime 4 and regime 5 care for the entire system's efficiency. Note that problems in these five regimes are all subject to the constraint of the SUE situation.

3.3 Modelling Techniques and Methods

3.3.1 Mesh Algorithm

The Mesh Algorithm (a heuristic method) was employed to solve the bi-level competition problem. The algorithm is used to numerically generate the best response curves τ_1 as a function of τ_2 (i.e. $\tau_1(\tau_2)$) and vice versa (i.e. $\tau_2(\tau_1)$), as discussed in section 2.1. τ_1 here represents the toll price that the Ambassador Bridge is going to set in reaction to the toll price set by The DRIC Bridge due to a given regime objective. Likewise, τ_2 represents the toll price that the DRIC Bridge is going to set in reaction to the toll price set by the Ambassador Bridge. The two curves could then be plotted to identify the intercept point demarking the equilibrium tolls prices. The Mesh Algorithm determines $\tau_1(\tau_2)$ and $\tau_2(\tau_1)$ taking into consideration cross-border flows that will be generated on both the Ambassador and DRIC Bridges under a particular τ_1 and τ_1 values.

Cross-border flows under the Mesh Algorithm could be simulated for any given pairs τ_1 and τ_2 that pertain to trucks and/or cars. As such, we simulate traffic flows under a range of toll prices τ_{1H} andτ_{2H}. Typically, we set a range and step-size increments for the toll prices on the two bridges. We then simulate the traffic flows for all possible toll pairs τ_1 and $\tau_2$on the two bridges. For instance, if the range is \$1 to \$4 with step-size increments of \$2 then we will simulate 9 traffic assignments for 9 pairs of toll prices, as shown in table 3.1.

Table 3.1 Example of Mesh Algorithm

Bridge 1 Toll Price (τ_1)	Bridge 2 Toll Price (τ_2)	Bridge 1 Revenue (R_1)	Bridge 2 Revenue (R_2)
0	0	100	110
0	2	120	90
0	4	160	50
2	0	90	120
2	2	100	110
2	4	115	95
4	0	50	160
4	2	95	115
4	4	100	110

Based on the data shown in table 3.1, the best response curve for the Bridge 2 can be obtained first. For example, when the toll price of Bridge 1 (τ_1) is fixed as 0, the best toll level of Bridge 2 can be identified as 0 since the Bridge's 2 revenue R_2 reaches its peak at that point (i.e. R_2 = 110). Therefore, the first point making the best response curve $\tau_1(\tau_2)$ is point (0, 0). Following the same logic, the toll price pairs for best response curve $\tau_1(\tau_2)$ can be determined. For Bridge 1, the best response curve can be also obtained by identifying its best toll level corresponding to each given toll level of Bridge 2.

In this thesis, the mesh algorithm is executed for a large number of toll pairs. Since the cost unit used in the COMMUTE simulation program is in minute, all the toll prices were converted into minute using predefined VOT factors. According to the VOT of heavy vehicles (H), a toll of $1.193 can be converted to 1 minute in the software. Accordingly, the range for the Mesh simulations is set from $1.193 (or 1 minute) to $119.3 (or 100 minutes) with an increment of $1.193 (i.e. 1 minute). A total of 10,000 (100×100) simulations were executed. In each simulation, cross-border traffic flow v_1 and v_2 on the two bridges were calculated for a given toll price pair (τ_{1H}, τ_{2H}). Each simulation run also provided the flow on all the links comprising the Windsor road network.

Since passenger vehicles trips also account for a significant portion of the total trips crossing the border, the role of passenger vehicle revenue should not be ignored. Therefore, a sensitivity analysis on passenger car toll level was performed, which will be discussed in the following chapter.

3.3.2 Traffic simulation

Given the Windsor Road network, intra-regional and cross-border travel demands, equilibrium toll prices on the Ambassador Bridge and DRIC Bridge are estimated for the regimes described earlier in this Chapter. A UTMS simulation model was utilized to estimate trips for cars and trucks for the year 2031. A Stochastic User Equilibrium (SUE) traffic assignment was then employed to determine equilibrium traffic flows for each Mesh simulation. The UTMS is executed using the COMMUTE modeling system. COMMUTE is a simulation program that executes the four-step models to generate traffic flows on the links forming a road network. Generally, COMMUTE enables the assessment of impacts such as congestion, energy use and environmental pollution due to the estimated traffic flow on the network. COMMUTE is also capable of performing a multi-class traffic assignment which simulates simultaneous traffic flow for passenger vehicles and commercial vehicles.

Given the emphasis on the border, our analysis focused on the two major players that use the border: private vehicles and heavy trucks. However, for the sake of comprehensiveness and to account for the role of other vehicles on the local road network, light and medium commercial vehicles were also considered. Eventually, solving the toll competition problem for more than two vehicle classes would prove to be a rather difficult modeling exercise. Therefore, we focused on solving the problem for two vehicle classes while accounting for the role of light and medium commercial vehicles. More specifically, trips pertaining to private vehicles and light commercial vehicles were grouped in one class that we refer to as **Cars**. On the other hand, medium and heavy commercial trips were also grouped in a second class that we refer to as **Trucks**. It was convenient to group light commercial vehicles with private vehicles since the former occurred only on local roads and did not cross the Canada-US border. Also, light commercial trips normally take place by small vehicles and therefore like private vehicles can utilize the entire road network. On the other hand, medium and heavy commercial vehicles are constrained to certain roads on the local road network and are normally carried out by large vehicles. Also, since the majority of the non-passenger traffic crossing the Canada-US border pertains to heavy commercial vehicles, grouping medium and heavy trucks was deemed appropriate. The trips for the two modeled vehicle classes were calculated as follows:

$$\text{Car Trips} = \text{Private Vehicle Trips} + 1.5\ \text{Light Commercial Trips} \tag{3.11}$$

$$\text{Truck Trips} = \text{Heavy Commercial Trips} + 0.8\ \text{Medium Commercial Trips} \tag{3.12}$$

The 1.5 factor in equation 3.11 suggest that one light commercial vehicle is equivalent to one and half passenger vehicles. This is an acceptable assumption since light commercial vehicles will normally have more pickup trucks and vans relative to regular size passenger vehicles. On the other hand, the 0.8 factor in equation 3.12 suggests that one heavy truck is equivalent to 1.25 medium trucks. Following Kanaroglou and Buliung (2008), the passenger car equivalent (PCE) factors for heavy and medium trucks is 2.5 and 2.0, respectively.

3.4 External Costs

In order to estimate the bi-level models and solve the toll competition problem the model required a number of parameters to describe tolls in terms of both monetary and time units. This section provides an overview on the work done to obtain those parameters.

3.4.1 Passenger toll level

Table 3.2 Passenger Vehicle Toll Price

Update Date	Toll ($)
2002-Jul-01	2.75
2007-Aug-18	3.75
2008-Feb-01	4.00
2009-Feb-01	4.00
2012-July-01	4.75
2013-Aug-15	5.00

We started by examining the historical trend of toll rates for passenger vehicles at the Ambassador Bridge. Table 3.2 provides the toll rates from 2002 to 2013. The reported values suggest that passenger toll rates increased over time and almost doubled within a period of approximately 10 years ($2.75 in 2002 to $5.00 in 2013).

Based on the toll records of year 2002 and 2013, the average annual growth rate from 2002 to 2013 can be calculated as 5.59%. Similar results can be found in Wilbur Smith (2010), who reported that the Ambassador Bridge's annual toll growth rate for passenger vehicles was 6.1% from 1989 to 1999, and 5.9% from 1999 to 2009.

3.4.2 Pavement Costs by Trucks

According to Hussain and Parker (2006), pavement costs could be estimated as a function of different factors of a project, including the standard, the vehicles' axle weights, and travel speeds, etc. As discussed by Holgu ń-Veras and Cetin (2009), pavement costs are made of the total expenditure of construction, maintenance and rehabilitation of the infrastructure. In the latter study, the pavement costs are simplified as a function of only three main factors: the total life cycle cost, the design standard of the facility and the load equivalency factors for each vehicle class.

For the two border crossing bridges in our study, the pavement deterioration could be attributed to both passenger and commercial vehicles. According to Chatti et al. (2004), traffic loads are a key component in pavement deterioration. However, considering heavy axle load to the pavement surface and axle configuration, trucks are the major contributors of roadway system damage (SSIT, 2000). Compared to passenger vehicles, trucks can cause more significant damage to highways and bridges, resulting in more frequent maintenance work (Bai, 2010). In our study, trucks account for a significant proportion of all the vehicles passing through the two bridges. Therefore, it is necessary to estimate the maintenance cost of the two bridges due to truck movements.

Although bridges have far more complicated structure than highways, their design codes and pavement expenditure are always discussed together in literature. To date, the most widely used codes in North America are the American Association of State Highway and Transportation Officials (AAHTO), Canadian Highway Bridge Design Code (CHBDC) and Ontario Highway Bridge Design Code (OHBDC). Although the requirements are quite different in some parts of Canadian and AASHTO provisions for highway bridges, they actually yield to similar principles. In the study performed by Bai (2010), pavement damage costs attributed to truck traffic were studied as one concept and a systematic pavement damage estimation procedure was developed to estimate the expenditure. In the NCHRP report by Fu et al. (2003), a highway cost allocation study from FHWA (1997) was applied to estimate the effect of truck weight on bridge network costs.

Many studies have already been performed to reveal the relationship between trucks and pavement damage of highways and bridges. In the study performed by Hajek and Agarwal (1990), it is shown that the amount of axle weight and wheel spacing contribute significantly to pavement damage. Chatti and Lee (2003) studied the effects of various trucks and axle configurations on flexible pavement fatigue using different summation methods (based on strain and dissipated energy) to calculate the damage. Bai et al. developed a systematic pavement damage estimation procedure to estimate the highway damage costs attributed to the truck traffic associated with the processed meat (beef) and related industries in southwest Kansas.

In the study performed by SSIT (2012), the FHWA's Highway Cost Allocation Study (2000) was recommended, since the relative costs attributable to each vehicle type are still valid now. In the FHWA's Highway Cost Allocation Study, pavement cost represents the contribution by different vehicle classes per mile's travel to pavement deterioration and the expenditure of rehabilitation, and the marginal costs for different vehicles on urban and rural Interstate highways were also estimated. The table is shown on the next page. The FHWA's highway cost allocation study (FHWA 2000) is actually an update of a previous one in 1982 (FHWA 1982). The new study developed bridge cost responsibility (in percentage) for different vehicle fleets. These responsibilities are applicable to federal expenditures on highway bridges. Four groups of costs were covered: new bridges, bridge replacement, major bridge rehabilitation, and minor bridge rehabilitation. Based on the FHWA's report, the truck damage deterioration level depends on load, axle configuration and location. In our study, since the study area is urban area and the truck group is combined by heavy commercial vehicles and medium commercial vehicles, a middle value between \$0.031 and \$0.409 will be referred for two bridges.

Additionally, in the study performed by Holgu ń-Veras and Cetin (2009), an analytical formulation was applied to calculate optimal tolls for different traffic classes. A well-developed model was proposed to estimate the pavement costs of highways, which could also be referred in our bridge study. The pavement fees caused by traffic level $Q_i$were computed based on the load equivalency factors (LEFs) for each vehicle type and the unit investment cost per equivalent single axle load (ESAL), as shown below.

$$\mathrm{C}_i^P = \sum_n \lambda_n \, Q_{i,n} \left(\frac{K}{L}\right) \mathrm{D}$$

In the above formula, λ_n represents the LEF for vehicle class n; L denotes the design number of ESAL repetitions; D represents the travel distance; K is the initial pavement investment; the term (K/L) denotes the unit investment cost per ESAL.

The selected LEF value for passenger vehicle was 0.0005 and for heavy truck was 2.4 in their study, which means the deterioration attributed to passenger vehicles can be ignored. In the analysis by Holgu ń-Veras and Cetin (2009), cost estimates per ESAL-mile (K/L) were set as \$0.05, \$0.30 and \$1.00 for Low, Medium and High scenarios. Based on this data, the pavement cost per mile for each truck can be obtained as:

Table 3.3 Range of pavement cost per mile per truck

Scenario	Cost per truck per mile ($)
Low	0.12
Medium	0.72
High	2.4

By comparison, it can be seen that the range shown in table 3.3 covered the pavement cost values ($0.031-$0.409) for multiclass truck recommended in the FHWA's report. Since the two bridges in our study are border crossings, a relatively conservative value of $0.70 was used. Since the total length of the two bridges is set as 1.42 miles, the $0.70 per truck per mile setting will give the pavement cost $1.00 per truck for both Ambassador Bridge and DRIC Bridge.

3.4.3 VOT estimation

As mentioned before, when no road user can reduce his/her travel cost by unilaterally changing route, an equilibrium condition is reached. In transport economics, the concept of value of time (VOT) stands for the opportunity cost of the time that a commuter spends on the journey (Kriger, et al., 2006). According to recent statistics, the hourly average wages for truck drivers in Canada ranges from $9.00 to $ 35.47, with an average hourly salary of $ 22.64 (Government of Canada, 2013). At the same time, the hourly average wages ranges from $15.84to $31.24 for heavy and tractor-trailer truck drivers in the USA, with an hourly mean wage of $19.40 (Bureau of Labor Statistics, 2012). With certain empirical conversion rates, the value of time of an area could be generated according to the average local income.

Essentially, travel time plays an important role in the general cost of any trip. To successfully explore the impacts of different price regimes on the cross-border network and identify the most feasible toll price regime, some empirical conclusions from previous studies will be adopted in this research. In the study performed by Wilbur Smith

(2010), calibrated logit models were applied to analysis the border crossing traffic of Windsor-Detroit area. The coefficients generated in their study are shown in table 3.4.

Table 3.4 Coefficients obtained in Wilbur Smith's Research (2010)

Coefficient	Units	Passenger Vehicles	Commercial Vehicles
Travel Time	Minutes	-0.089	-0.068
Travel Cost	Dollars	-0.526	-0.057

Table 3.5 VOT values for different vehicle groups

Vehicle	VOT ($/min)	TOLL ($)	TOLLCOST(min)
P	0.17	4.75	28.07
L	1.19	6.50	5.45
M	1.19	11.25	9.43
H	1.19		

As can be seen from table 3.4, the VOT values for different vehicle groups can be calculated. For instance, for passenger vehicles, the VOT value can be obtained by dividing the minutes coefficient (-0.089) by the cost (dollars) coefficient (-0.526). Table 3.5 summarizes the VOT values for passenger and commercial vehicles, which were adopted in this thesis.

It should be mentioned that the above toll prices for passenger, light commercial and medium commercial vehicles are based on the current toll price setting on Ambassador Bridge. In this study, except for heavy commercial vehicles, toll prices for all the other vehicle groups for both bridges are fixed. According to Kriger et al. (2006), trucks and other commercial vehicles are charged much higher (200% - 1,000%) than automobile at toll facilities. Due to the larger size and higher toll rates, commercial vehicles have a greater impact on the competition between toll roads. For this reason, this study will focus more on the analysis for commercial vehicles.

CHAPTER Ⅳ

RESULTS & DISCUSSION

4.1 Introduction

This chapter presents the results of the bi-level toll competition problem solved by the methods discussed in Chapter 3. Outputs from the individual Mesh simulations are not reported in this thesis. Instead, the material presented in the chapter is focused on reporting the best response curves that were generated from the Mesh Simulations. Also, a number of individual simulations were extracted and analyzed to illustrate the sensitivity of the model to various important exogenous parameters such as: passenger car tolls, truck pavement cost and changes in the Value of Time (VOT) of trucks.

This chapter consists of four sections. Section 4.2 provides the details of the sensitivity analyses performed to assess the impacts of some of the exogenous parameters used in the model. The sensitivity analysis was also employed to identify the values of the exogenous parameters that were used to execute the five toll price regimes. Section 4.3 presents the simulation results obtained from regimes 1 to 5, while section 4.4 provides a comparison and a discussion of the results from these five regimes. The final section of this chapter gives a summary of the modeling work.

4.2 Exogenous model parameters

All the parameter values were transferred to monetary units before running the simulation in the model. Sensitivity analyses were performed using regime 1, where competition between the two bridges dictates the system. The analyses allowed us to see the impact of the values of the following parameters: the passenger vehicle toll τ_P, the per-truck pavement cost m and the VOT of trucks β_H.

4.2.1 Passenger vehicle toll analysis

When considering toll competition between the Ambassador Bridge and the DRIC Bridge, passenger vehicle revenue plays a significant role. As such, we tested passenger vehicle toll price levels for four cases: $5, $7.5, $10, and $12. Consequently, four scenarios of traffic simulation (for the 4 passenger vehicle toll price cases) were executed under regime 1. In each case, 10000 (100×100) simulations were executed to engage the Mesh Algorithm. Because of government policy restrictions, it is assumed that the operators of the two bridges have the same passenger tolls on the two bridges in each case.

Figure 4.1 illustrates the best response curve for scenario 1 when the passenger toll is $5. Note that the pavement cost is fixed at $0.72 per truck per mile and the VOT for trucks was set as $1.19 per minute for these four cases. As can be seen, the grey curve 1(2) represents the best response curve of Ambassador Bridge as a function of the toll price of the DRIC, while the black curve 2(1) denotes the DRIC's best response curve with given toll price of the Ambassador Bridge. Using Mesh method, the best toll level of one bridge can be numerically determined as a result of setting a given toll level of the other bridge. Obviously, both curves are upward-sloping curves, interacting at the common point around (15.14, 18.81), indicating that when the passenger toll price is set as $5 for both bridges, the equilibrium toll price will be about $15.14 and $18.81 for the Ambassador Bridge and the DRIC Bridge respectively. Currently, the average toll cost for each heavy commercial vehicle is $26.25 for Ambassador Bridge, which is distinctly higher than the estimated equilibrium toll prices in case 1.

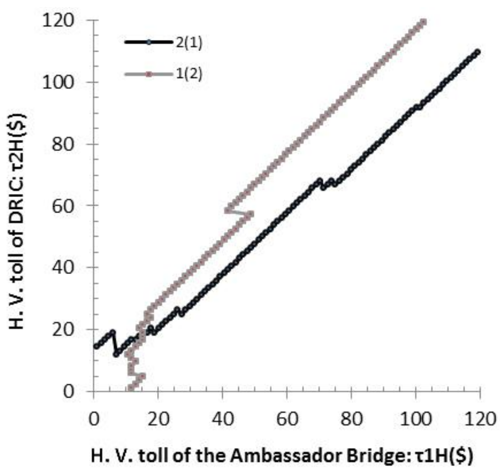

Fig. 4.1 Best response curve for case 1

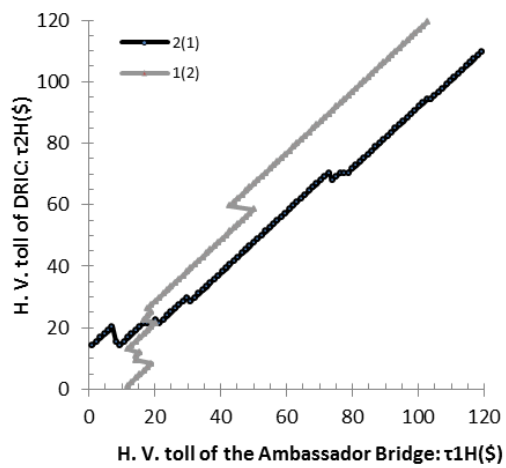

Fig. 4.2 Best response curve for case 2

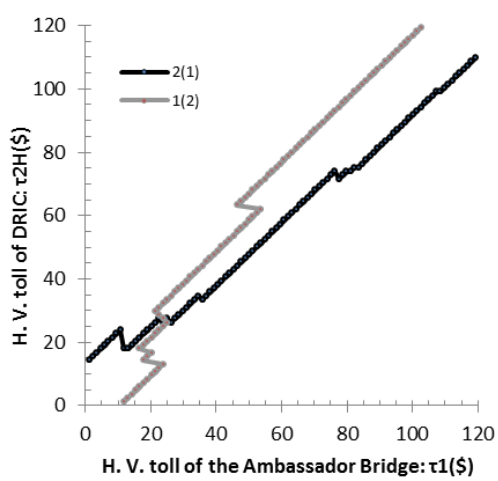

Fig. 4.3 Best response curve for case 3

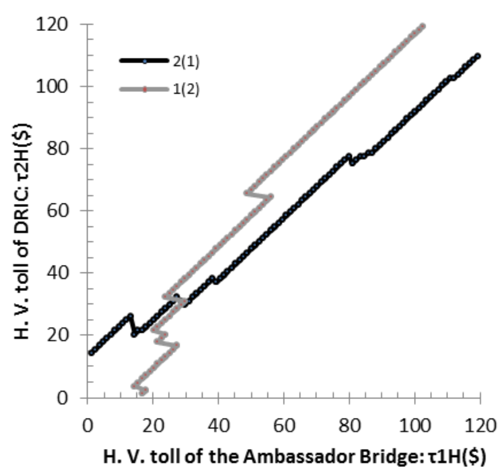

Fig. 4.4 Best response curve for case 4

Figure 4.2 presents the best response curves for both bridges when the passenger toll price is set as $7.5. Higher equilibrium toll prices are obtained in this case, at approximately (19.09, 22.67). Compared with scenario 1, the equilibrium toll prices generated in this scenario are closer to the current average truck toll in the study area. Figures 4.3 and 4.4 demonstrate the best response curve pertaining to passenger tolls $10 and $12.5, respectively. From figure 4.8, we can read that the equilibrium of the competition appears around the point (23.05, 25.62). In figure 4.4, the two best response curves interact at the point (27.00, 29.57).

From the figures demonstrated above, it can be seen that the equilibrium toll price of heavy vehicle for the two bridges is increasing with the increase of passenger toll price.

Table 4.1 shows the common points and the corresponding total revenue data obtained from the passenger vehicle toll sensitivity analysis. As expected, along with the growth of passenger vehicle toll price, the equilibrium truck tolls of the two bridges also increase from case 1 to case 4. When the passenger toll is set as $5, the equilibrium was reached when the Ambassador Bridge set its heavy vehicle toll to $15.14 and the DRIC Bridge set it to $18.81, which might be a relatively low value for the simulated year 2013. At the same time, the generated equilibrium truck toll price as well as the given passenger vehicle toll $12.5 in case 4 is also not realistic when compared with the former two cases.

Table 4.1 Best response curve data for passenger toll analysis

(A: Ambassador Bridge; D: DRIC Bridge)

Passenger Toll($)	Equilibrium Truck Toll ($)		Total Revenue ($)		P.V. Flow		H.V. Flow	
	A	D	A	D	A	D	A	D
5.0	15.14	18.81	30642.65 (39.38%)	42932.13 (60.62%)	2154 (45.17%)	2615 (54.83%)	1362 (44.17%)	1721 (55.83%)
7.5	19.09	22.67	40786.21 (41.75%)	56898.23 (58.25%)	2154 (45.17%)	2615 (54.83%)	1362 (44.17%)	1721 (55.83%)
10.0	23.05	25.62	49430.16 (40.98%)	71274.93 (59.02%)	2472 (51.85%)	2296 (48.15%)	1120 (36.35%)	1962 (63.65%)
12.5	27.00	29.57	61158.26 (42.98%)	86730.41 (57.02%)	2472 (51.85%)	2296 (48.15%)	1120 (36.35%)	1962 (63.65%)

Another aspect to look at is the influence of different passenger toll levels on the total revenue. It is shown in table 4.1 that although the increase of passenger vehicle toll induces growth in the total revenue of the two bridges, the market share of each bridge stays stable. This can be explained by the fact that under SUE condition passenger vehicles' traffic assignment will remain stable so long as the passenger toll prices of these two bridges are always the same. The numerical results from the equilibrium toll competition problem suggest that the DRIC Bridge will be more attractive and competitive than the Ambassador Bridge.

Additionally, it is worthwhile noting that the traffic assignment in case 1 is the same as in case 2. At the same time, cases 3 and 4 also generate the same trip distribution for both passenger vehicles and trucks. In order to test the elasticity of the trip distribution with the change of passenger toll, three additional scenarios are performed with relatively extreme passenger toll values: $0, $ 20 and $30 respectively.

Table 4.2 Best response curve data for additional passenger toll analysis

(A: Ambassador Bridge; D: DRIC Bridge)

Passenger Toll($)	Equilibrium Truck Toll ($)		Total Revenue ($)		P.V. Flow		H.V. Flow	
	A	D	A	D	A	D	A	D
0.0	7.16	10.74	30642.65 (33.35%)	42932.13 (66.65%)	2154 (45.17%)	2615 (54.83%)	1362 (44.17%)	1721 (55.83%)
20.0	39.37	40.56	93953.91 (43.45%)	122286.27 (56.55%)	2942 (61.7%)	1826 (38.3%)	915 (29.68%)	2168 (70.32%)
30.0	52.49	57.26	132440.20 (42.92%)	176165.84 (57.08%)	1573 (32.99%)	3196 (67.01%)	1656 (53.70%)	1427 (46.30%)

Table 4.2 shows the results of the three additional passenger toll prices. Compared to table 4.1, it can be seen that there is no difference in trip distribution among the three passenger toll scenarios: $0, $5 and $7.5. In contrast, the passenger toll scenario of $20 generates the same trip distribution results with as the $10.0 and $12.5 passenger toll scenarios. However, when the passenger toll is as high as $30, the flow assignment is totally different. While the revenue shares of the two bridges are still similar to the $20 passenger toll case, a noticeable switch in passenger and truck assignment appears in the $30 passenger toll scenario. This could be explained by the fact that when the toll for passenger vehicles is extremely high on both bridges, the equilibrium truck toll could be quite high and the gap between the truck tolls on the two bridges will also swell. As a result of the enlarged truck toll gap, more trucks will turn to choose the Ambassador Bridges instead of the DRIC Bridge, which could drive away a number of passenger vehicles from the Ambassador Bridge as well.

By observing the results of all the passenger toll analysis scenarios, we can see that within a reasonable range, the share of truck trips of the DIRC Bridge would experience an increase when the passenger toll prices on both bridges become higher than $7.5. Nevertheless, when the passenger toll price is extremely high, more trucks will be attracted by the Ambassador Bridge since the difference between the equilibrium truck toll prices will also become very large.

According to Statistics Canada, the Consumer Price Index (CPI) value for transportation changed by 0.8% from 2012 to 2013. Based on the 0.8% CPI, the projected future passenger vehicle toll would be very low, that is, reaching a total of approximately$5.77 in 2031. However, $5.77 is perceived to be on the low end for a planning horizon of approximately 20 years. Based on the above results, the medium-low value of $7.5 from table 4.1 was selected as the fixed passenger toll to run the subsequent simulations.

4.2.2 Pavement cost analysis

For the two border crossing bridges in our study, pavement deterioration can be caused by both passenger and commercial vehicles. However, trucks account for a significant proportion of all the vehicles passing through the two bridges (i.e. 39%) and that portion magnifies given the more pronounced impact of trucks on pavement when compared to regular passenger vehicles. Therefore, it is necessary to estimate the cost associated with pavement deterioration due to trucks.

To figure out the ideal pavement cost parameter, regime 1 is simulated under different pavement cost values. Based on chapter 3, a medium value of $0.7 was identified as the pavement cost per truck per mile. Therefore, the pavement cost per truck for both

Ambassador Bridge and DRIC Bridge is estimated to roughly $1 since the total length of the two bridges is approximately 1.42 miles (i.e. 2.29 km). Next, four scenarios representing four pavement costs including $1 per truck are tested.

Table 4.3 Best response curve data for pavement cost analysis

(A: Ambassador Bridge; D: DRIC Bridge)

Pavement Cost ($ per truck)	Equilibrium Truck Toll ($)		Total Revenue ($)		P.V. Flow		H.V. Flow	
	A	D	A	D	A	D	A	D
0.0	19.09	20.28	39532.95 (40.67%)	57660.77 (59.33%)	2942 (61.70%)	1826 (38.30%)	915 (29.68%)	2168 (70.32%)
1.0	19.09	22.67	40786.21 (41.75%)	56898.23 (58.25%)	2154 (45.17%)	2615 (54.83%)	1362 (44.17%)	1721 (55.83%)
2.0	20.28	23.86	41049.01 (41.77%)	57230.39 (58.23%)	2154 (45.17%)	2615 (54.83%)	1362 (44.17%)	1721 (55.83%)
3.0	21.45	25.05	41311.82 (41.78%)	57562.54 (58.22%)	2154 (45.17%)	2615 (54.83%)	1362 (44.17%)	1721 (55.83%)

Table 4.3 summarizes the simulation results of the pavement cost analysis with respect to the change of the pavement cost. It can be seen that the toll prices of the two bridges grow slightly with the increase in pavement cost. However, it can also be seen that the pavement cost parameter has even less influence on the distribution of total revenue than the passenger toll. Although there is a slight increase of total revenue with the increase of pavement cost for each bridge, the market share of the Ambassador Bridge and the DRIC Bridge is always around 40% and 60%, respectively. This could be due to the similar generated equilibrium truck tolls in these four pavement cost scenarios. The results suggest that after the first scenario, all the following scenarios generate the same trip distributions among the two bridges. To examine the elasticity of the pavement cost

parameters, two extreme scenarios are simulated with pavement costs of $0.5 and $10 per truck, as shown in table 4.4.

Table 4.4 Best response curve data for additional pavement cost analysis

(A: Ambassador Bridge; D: DRIC Bridge)

Pavement Cost ($ per truck)	Equilibrium Truck Toll ($)		Total Revenue ($)		P.V. Flow		H.V. Flow	
	A	D	A	D	A	D	A	D
0.5	19.09	22.67	41467.05 (41.75%)	57758.73 (58.25%)	2154 (45.17%)	2615 (54.83%)	1362 (44.17%)	1721 (55.83%)
10.0	28.63	32.21	41526.96 (41.79%)	57834.48 (58.21%)	2154 (45.17%)	2615 (54.83%)	1362 (44.17%)	1721 (55.83%)

The results indicate no difference in the traffic flow assignment when considering the new pavement cost values. As expected, the equilibrium truck tolls on the two bridges are still found to increase with the rise of pavement cost, and the market share of the two bridges is still around 40% and 60% respectively. This indicates that the change of the pavement cost will only affect the equilibrium truck price level, but will have little influence on the revenue and trip distribution. In the two-link example discussed in Chapter 3, it is found that the change of the pavement cost will only change the equilibrium toll prices but will have no influence on the revenue, i.e., one unit increase in pavement cost will simply result in one unit increase in equilibrium toll level, or, in other words, the pavement cost is simply transferred to the road users by the road operators. In contrast, here from table 4.3 and 4.4, we can see that the equilibrium revenue of both bridges can increase a bit with the pavement cost. This is because the competition problem in this research is under non-linear cost function and one unit increase in pavement cost could lead to more than one unit increase in equilibrium toll.

Figure 4.5 to 4.8 illustrate the best response curves for regime 1 when the pavement cost increase from \$0 to \$2.1 per truck per mile (\$0 to \$3.0 per truck). Note that the passenger vehicles toll is fixed as \$7.5 and the VOT for heavy vehicle class is set as \$1.193/min in these four cases.

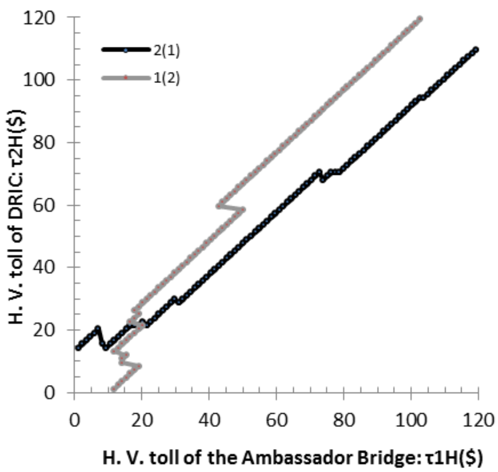

Fig. 4.5 Best response curve for case 1

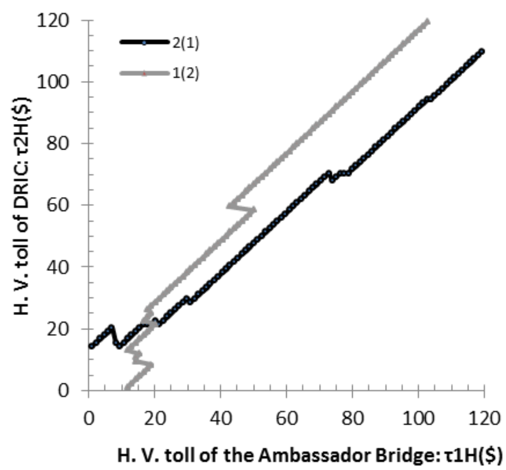

Fig. 4.6 Best response curve for case 2

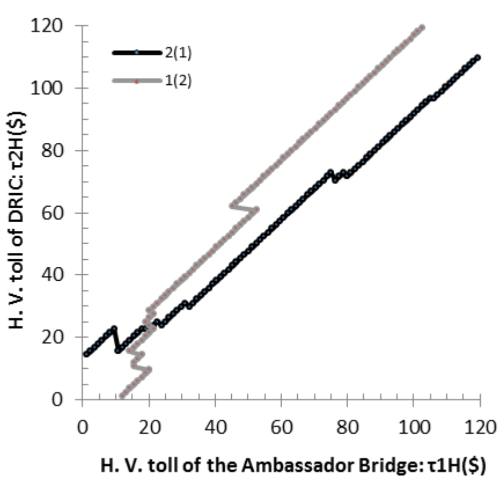

Fig. 4.7 Best response curve for case 3

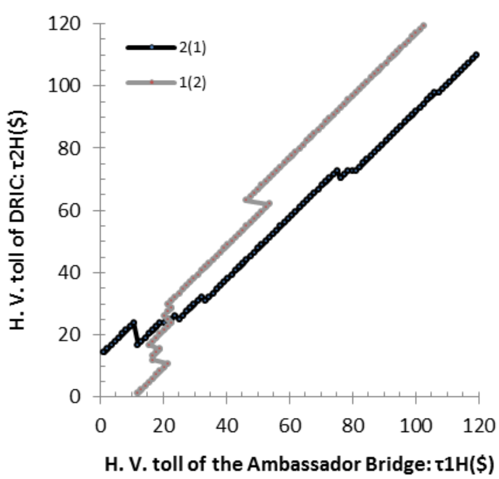

Fig. 4.8 Best response curve for case 3

Similar with the passenger toll analysis section, the grey curve 1(2) denotes the best response curve of Ambassador Bridge as a function of the toll price of the DRIC Bridge, and the black curve 2(1) is the DRIC's best response curve as a function of the toll price of the Ambassador Bridge.

From figure 4.5 to 4.8, it can be seen that there is an increasing trend of the equilibrium prices with the growth of pavement cost. However, the change caused by the increase of pavement cost is relatively weak compared with the passenger toll factor. From case 1 to case 4 in this section, the pavement cost raises from 0 to $2.1 per truck per mile, but the change of the equilibrium toll is not very significant. Based on the sensitivity analysis and the findings from past studies, the medium value of $0.70 per truck per mile was chosen as the fixed pavement cost parameter in this research.

4.2.2 Truck VOT analysis

In this section, the truck VOT sensitivity analysis based on the results of regime 1 is performed. Four different scenarios are simulated to figure out the influence of the truck VOT parameter on the toll competition. In each scenario, the passenger toll is fixed as $7.50 and the pavement cost is given as $0.70 per truck per mile.

For case 4, the VOT value for trucks is estimated based on the data given by Wilbur Smith (2010). Since the VOT for case 4 is nearly $70 per hour, a relatively high value, the testing values of the first three cases are set as $40, $50 and $60 per hour, corresponding to the values of $0.667, $0.833 and $1.000 per minute, respectively.

Table 4.3 lays out the numerical results of regime 1's subcases for truck VOT analysis. It can be seen that when the VOT of heavy vehicles increase, the change of total revenue distribution is quite slight as well as the equilibrium truck tolls. It can also be found that the trip distributions in the first three scenarios are totally the same. In order to collect additional data to explain this observation, four additional experiments with a wider range of VOT values of $0.5, $2, $3 and $4 per minute are performed.

Table 4.3 Best response curve data for Truck VOT analysis

(A: Ambassador Bridge; D: DRIC Bridge)

Truck VOT ($ per minute)	Equilibrium Truck Toll ($)		Total Revenue ($)		P.V. Flow		H.V. Flow	
	A	D	A	D	A	D	A	D
0.67	17.33	18.67	37282.58 (42.05%)	51378.43 (57.95%)	2415 (50.63%)	2354 (49.37%)	1173 (38.08%)	1909 (61.92%)
0.83	17.50	19.17	37478.22 (41.73%)	52332.82 (58.21%)	2415 (50.63%)	2354 (49.37%)	1174 (38.08%)	1909 (61.92%)
1.00	19.00	21.00	39239.05 (41.27 %)	55832.25 (58.73%)	2415 (50.63%)	2354 (49.37%)	1174 (38.08%)	1909 (61.92%)
1.19	19.09	22.67	40786.21 (41.75%)	56898.23 (58.25%)	2154 (45.17%)	2615 (54.83%)	1362 (44.17%)	1721 (55.83%)

Table 4.4 shows the simulation results of the four additional scenarios. Compared with the four scenarios shown in table 4.3, we can see that when VOT increases from $0.50 to $4.00, there is a general increase trend in the revenue share of the DRIC Bridge. When the VOT is as low as $0.50, it is found that more trucks would like to choose the Ambassador Bridge, even though the advantage is not quite significant. At the same time, the DRIC attracts a large part of passenger vehicles. This can be explained by the fact that when the VOT is very low, the influence of the travel time will be reduced and lower toll price will be more attractive to the truck drivers. After the $0.50 scenario, although

there are some small fluctuations, the trip distributions are found to be stable with the change of the VOT.

Table 4.4 Best response curve data for additional VOT analysis

(A: Ambassador Bridge; D: DRIC Bridge)

VOT ($ per minute)	Equilibrium Truck Toll ($)		Total Revenue ($)		P.V. Flow		H.V. Flow	
	A	D	A	D	A	D	A	D
0.5	16	18	36631.33 (43.17%)	48228.73 (56.83%)	1573 (32.99%)	3196 (67.01%)	1656 (53.70%)	1427 (46.30%)
2.0	24	30	47474.74 (40.58%)	69518.33 (59.42%)	2154 (45.17%)	2615 (54.83%)	1362 (44.17%)	1721 (55.83%)
3.0	33	39	55673.47 (38.17%)	90199.33 (61.83%)	2415 (50.63%)	2354 (49.37%)	1174 (38.08%)	1909 (61.92%)
4.0	36	48	63814.85 (38.84 %)	100496.23 (61.16%)	2154 (45.17%)	2615 (54.83%)	1362 (44.17%)	1721 (55.83%)

Based on the sensitivity analysis and the findings from past studies (Wilbur Smith, 2010), a relatively high value of $1.193 per minute was selected as the truck VOT in this study.

4.3 Simulation Results of Different Competition Regimes

In Chapter 3, five different competition regimes between the two bridges were explained in detail: for Regime 1, both bridges aim at maximizing their profits; for Regime 2, the operator of DRIC Bridge wants to minimize the total travel cost of heavy trucks on the two bridges while the Ambassador Bridge's concern is still profit maximization; Regime 3 is quite similar to Regime 2, the only difference is the travel cost minimization problem also includes the passenger vehicle group; in Regime 4, the objective of the DRIC

Bridge's operator is to minimize the heavy vehicle group's travel cost in the entire system; for Regime 5, the DRIC's system travel cost minimization objective also takes the passenger vehicle group into consideration.

Table 4.5 Simulation structure of Regime 1

(A: Ambassador Bridge; D: DRIC Bridge)

Simulation Run	Passenger Toll ($)	Pavement Cost ($ per mile per truck)	VOT of Truck ($ per minute)	Truck Toll ($)	
				A	D
1	7.5	0.7	1.193	1.19	1.19
⋮	7.5	0.7	1.193	⋮	⋮
10000	7.5	0.7	1.193	119	119

In this section, using the Mesh method and the selected model parameter values, the competition equilibrium of each regime was numerically identified. Table 4.5 shows the framework of the mesh method in this study. That is, by changing the toll levels of both bridges from $1.193 to $119.3 at a step-size of $1.193, the best-response curve of each bridge as a function of the other bridge's toll level was generated to solve the equilibrium toll competition problem.

4.3.1 General comparison of simulation results

Table 4.6 summarizes the equilibrium results of the five competition regimes, from which we can see that the equilibrium results of Regime 2 and Regime 3 are exactly the same, while Regime 4 and Regime 5 also generate identical results with each other. This observation is not a coincidence, but resulted from the disparity in the VOT of the passenger vehicles and the heavy commercial vehicles. That is, because the passenger car

VOT is much smaller than the truck VOT, the equivalent change in monetary cost brought by one minute change of the passenger vehicle travel time is much smaller than that brought by one minute change of the truck travel time. As a result, taking passenger car travel time into consideration in Regime 3 and 5 will not have much impact on the optimal strategy of DRIC as compared to Regime 2 and 4.

Table 4.6 Best response curve data of different truck toll regimes

(A: Ambassador Bridge; D: DRIC Bridge)

Regime	Equilibrium Truck Toll ($)		Total Revenue ($)		P.V. Flow		H.V. Flow	
	A	D	A	D	A	D	A	D
1	19.09	22.67	40786.21	56898.23	2154	2615	1362	1721
2	17.90	19.09	37526.32	52907.10	2942	1826	915	2168
3	17.90	19.09	37526.32	52907.10	2942	1826	915	2168
4	15.51	11.93	32295.21	38253.82	3717	1052	304	2778
5	15.51	11.93	32295.21	38253.82	3717	1052	304	2778

To see the above explanation more clearly, let us take consider one iteration of the Mesh method to compare the best responses of DRIC under Regime 2 and under Regime 3. Consider the Ambassador Bridge's truck toll is fixed at $\tau_{1H} = \$17.90$, then figure 4.9 shows how the objective functions of Regime 2 and Regime 3 of DRIC change when its truck toll changes. From figure 4.9, we can see that the shapes of the two objective functions are identical, both attaining optimality (minimum objective function value) at τ_{2H}=16 minutes (or $19.10). Thus it is verified that, whether DRIC considers trucks only (under Regime 2) or considers both trucks and passenger cars (under Regime 3), its optimal strategy is the same, i.e., it should set a truck toll $\tau_{2H} = \$19.10$ in both cases given the Ambassador Bridge's truck toll $\tau_{1H} = \$17.90$. Similarly, it can be verified that the best responses of DRIC under Regime 4 and under Regime 5 are the same.

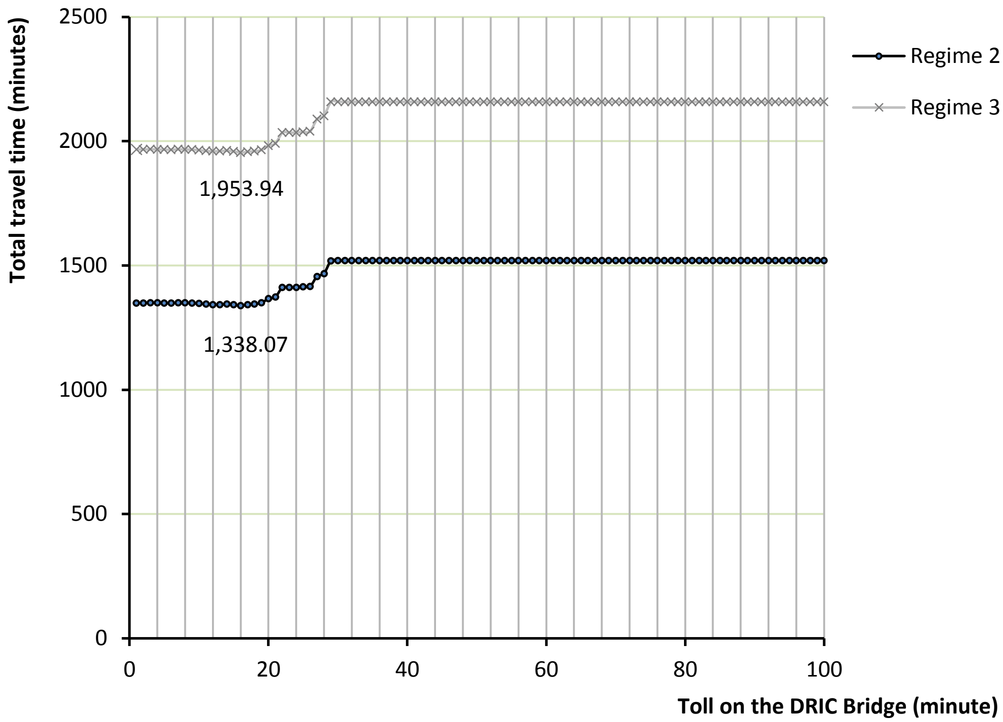

Fig. 4.9 Objective functions of DRIC under Regime 2 and Regime 3 given $\boldsymbol{\tau_{1H}} = \$\mathbf{17.90}$

Using the same simulation iteration as in figure 4.9, figure 4.10 compares the obtained travel time of different vehicle groups in Regime 3. Obviously, the travel time of the passenger vehicles is very high before being converted into monetary cost. However, compared to the heavy vehicle group, the fluctuation of the passenger vehicles' travel time curve is too mild to affect the total travel time curve. Thus, even though the travel time of passenger vehicles is taken into account in Regime 3, the best response curve is still the same with the Regime 2. For Regime 5, the situation is in the same fashion. The outcomes of Regime 3 and Regime 5 also show that the total travel time of passenger vehicles is not very sensitive to the change to truck toll.

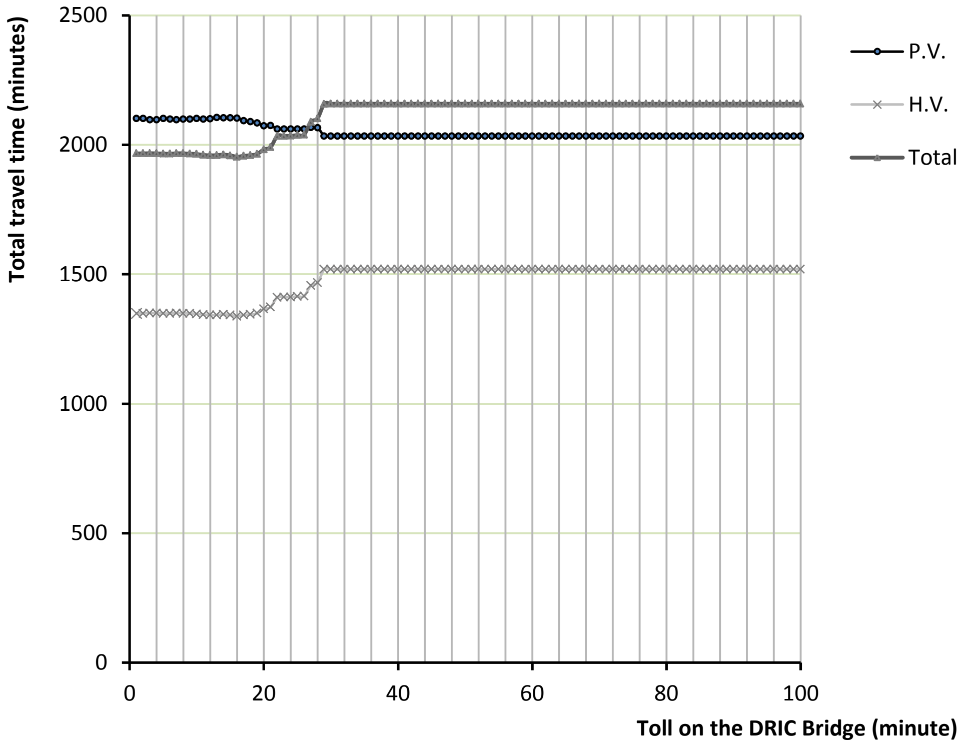

Fig. 4.10 Travel time of different vehicle groups of a sample from Regime 3

In summary, because the truck VOT is much higher than the passenger car VOT, whether DRIC considers minimizing truck travel time only, or it considers minimizing the monetary delay of trucks and passenger cars, its decision making should not change. This means the five regimes actually reduce to three regimes only. Therefore, from now on, when comparing different regimes, we only refer to Regime 1, Regime 3 and Regime 5.

Figure 4.11 presents the best response curve of the Ambassador Bridge, $\tau_{1H}(\tau_{2H})$ (marked as 1(2) in figure 3), and three different best response curves of DRIC, $\tau_{2H}(\tau_{1H})$ (marked as 2(1) in figure 3) under Regime 1, 3 and 5. Note that the intersection between $\tau_{1H}(\tau_{2H})$ and each $\tau_{2H}(\tau_{1H})$ represents the truck toll equilibrium under each regime.

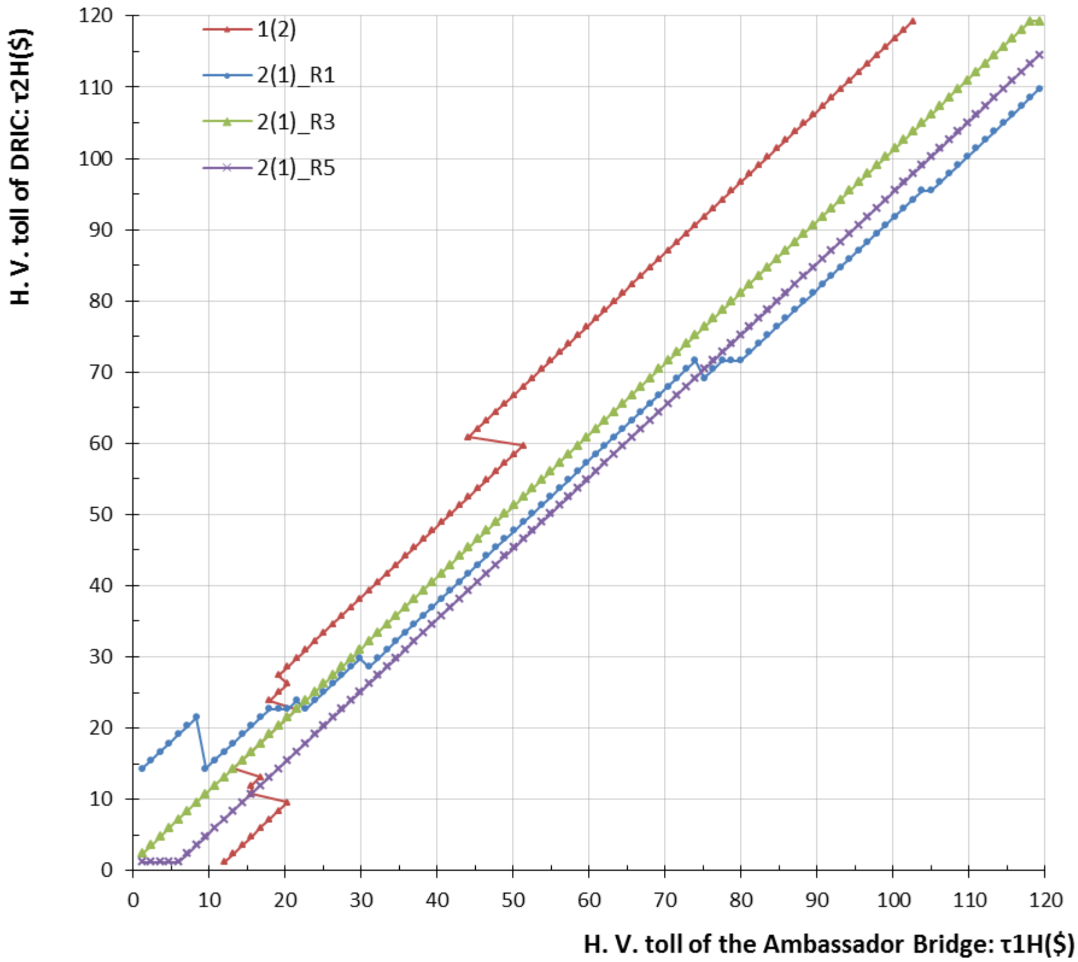

Fig. 4.11 Best response curves for regime 1, 3 and 5

By comparing the best response curves of DRIC under Regime 3 and under Regime 5, it can be seen that these two curves are parallel to each other, and both of them intersect with the Ambassador Bridge's curve at a lower point than Regime 1. This indicates that when the operator of DRIC focuses on the improvement of border-crossing network efficiency, the toll competition will lead to lower truck toll prices on both bridges.

4.3.2 Specialized comparison of the simulation results

Revenue and Equilibrium Toll Comparison

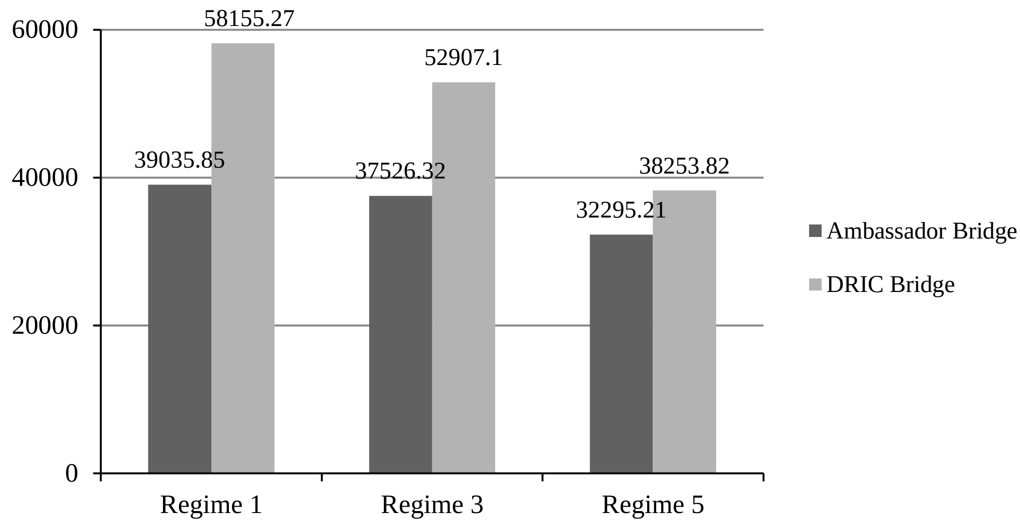

Fig. 4.12 Total Revenue Comparison of Different Regimes

Figure 4.12 illustrates the comparison of total revenue under the three regimes. Generally, both bridges experience a decrease in profit from Regime 1 to Regime 5. For Regime 3 and Regime 5, since the objective of the DRIC is not for profit, the operator of the DRIC could choose sacrificing the advantage in revenue to improve the travel time in the study area. However, since the objective of the Ambassador Bridge is profit maximizing for all of these regimes, the most beneficial competition mode is supposed to be the one with highest total revenue. According to figure 4.12, it can be seen that the Ambassador Bridge's profit peak appears in Regime 1, with 39035.85 dollars. This indicates that after the new bridge is completed, the highest equilibrium revenue of Ambassador Bridge will only occur when the DIRC Bridge also goes for profit in the competition.

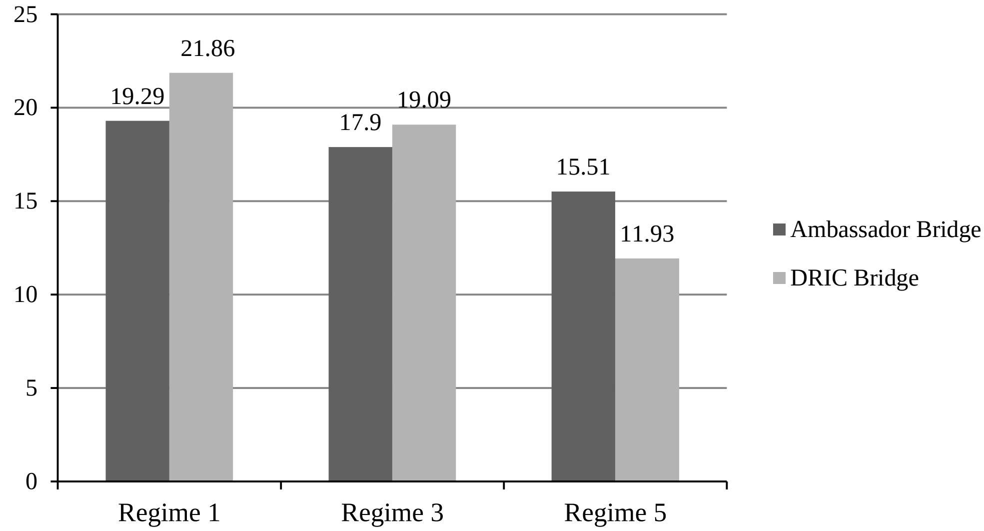

Fig. 4.13 Equilibrium Toll Comparison of Different Regimes

Figure 4.13 shows the comparison of the equilibrium truck tolls of these three regimes. It can be seen that, from Regime 1 to Regime 5, there is a more significant decreasing trend of the toll price on DRIC as compare to the Ambassador Bridge. This is because the design capacity of the DRIC Bridge is considerably larger than the Ambassador Bridge, and the system congestion level can be decreased if more trucks are attracted to DRIC by its lower tolls.

Trip Distribution Comparison

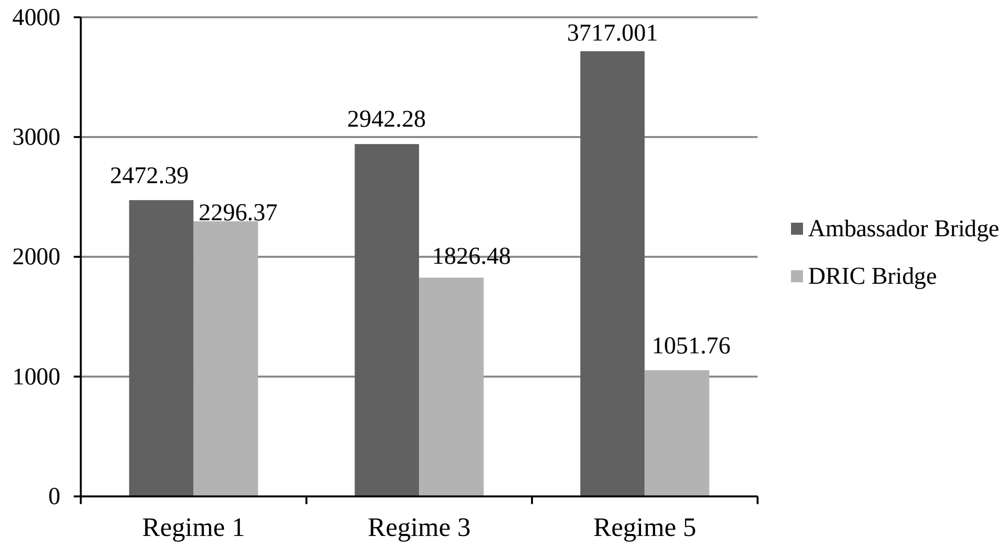

Fig. 4.14 Passenger Vehicle Trip Distribution Comparison of Different Regimes

Figure 4.14 provides the comparison of the passenger vehicle trip distribution among different regimes. As can be seen from the figure, the Ambassador Bridge attracts the highest passenger vehicle volume in Regime 5, when the operator of the DRIC Bridge plans to minimize the entire traffic system's travel time. On the other hand, the peak of passenger vehicle volume of DRIC Bridge appears in the first regime, when both bridges compete for the profit.

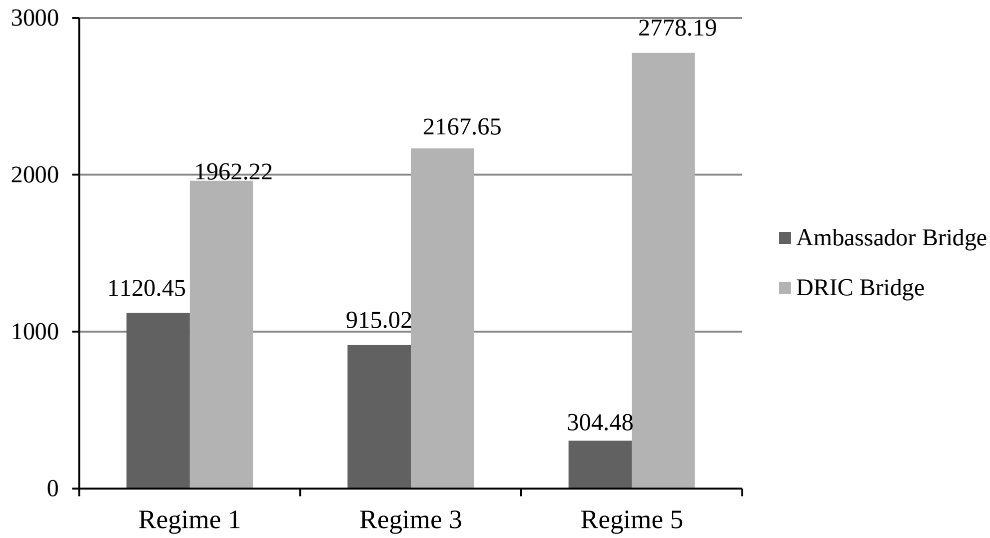

Fig. 4.15 Truck Trip Distribution Comparison of Different Regimes

Figure 4.15 gives the comparison of the truck trip distribution among different regimes. It can be seen that the truck volume of the Ambassador Bridge experiences a dramatic decrease from Regime 1 to Regime 5. On the contrary, in the last regime, the truck trip rate on the DRIC Bridge reaches the highest point. This indicates that when most trucks are assigned to the DRIC Bridge during the competition, the transportation system efficiency of the border crossing area is the highest.

CHAPTER V

CONCLUSION

5.1 Overview

A new publicly-owned cross-border bridge over the Detroit River between Windsor, Ontario and Detroit, Michigan is planned to be built by the year 2020. The competition between the new bridge (named New International Trade Crossing (NITC), or Detroit River International Crossing (DRIC)) and the existing bridge (the Ambassador Bridge) will have significant impact on international trade and border-crossing traffic between Canada and US. In this paper we model the competition between the two bridges as a duopoly game where each bridge's strategy is its toll level.

Due to political constraint, we assume that both bridges will set their passenger car tolls at the highest politically-acceptable level. As such, the passenger car tolls of the two bridges are the same and exogenously given. This assumption is reasonable given that the Ambassador Bridge and the Detroit-Windsor Tunnel charge the same passenger car toll for most of the time. With this assumption, each bridge's strategy reduces to its truck toll level, and the competition equilibrium (i.e. Nash equilibrium) emerges when each bridge cannot improve its objective function by unilaterally changing its truck toll level.

For the Ambassador Bridge, as a privately-owned bridge, its objective function is naturally profit maximization. However, since the new bridge is a publicly-owned bridge it may have different objectives, or, at least profit maximization should not be considered as its only option. In this paper, we consider five different objective functions for the new bridge, which will give five different competition regimes between the two bridges.

5.2. Modeling Approach

Based on official projections, region-wide growth in population and employment has been estimated for the period 2006-2031. The allocation of this growth across the different traffic analysis zones (TAZ) was based on the work reported in Gingerich et al. (2014). PM Peak Hour (4 PM) trip productions and attractions for each zone were estimated to create future demand Origin-Destination matrices for the year 2031 for passenger vehicles (PV) as well as light (LV), medium (MV) and heavy (HV) commercial vehicles. Given the emphasis on the border, our analysis focused on the two major players that use the border: private vehicles and heavy trucks.

The competition between the two bridges has a natural bi-level structure, with the upper level being the two bridges setting their respective tolls, and the lower level being the road users (cars and trucks) choosing their routes. This gives rise to an equilibrium problem with equilibrium constraints (EPEC problem). We model the upper level competition equilibrium using the traditional Nash equilibrium concept, i.e., at equilibrium each bridge cannot improve its objective function by unilaterally changing its strategy (i.e. truck toll). The lower level traffic equilibrium is modeled as a multi-class logit-based stochastic user equilibrium (SUE), where the logit SUE parameter for trucks is set to be sufficiently large so that each truck will choose the shortest path.

We assume the Ambassador Bridge always wants to maximize its profit, while the new bridge may have various objective functions including: (1) maximization of profit, (2) minimizing overall travel time of trucks over the two bridges, (3) minimizing the total monetary cost of the travel time of both trucks and passenger vehicles over the two bridges, (4) minimizing the network-wide total travel time of trucks, or (5) minimize the network-wide total monetary cost of the travel time of both trucks and passenger cars.

We employ the Mesh method to solve the bi-level competition problem. This is done by simulating a multi vehicle-class SUE traffic assignment under a range of truck tolls for both bridges. Specifically, we change the truck toll of each bridge from 1 minute to 100 minutes at an incremental step-size of 1 minute. This is equivalent to monetary value from \$1.19 to \$119 at a step-size of \$1.19, given the truck VOT parameter $\beta_H = \$1.19$ per minute. Such approach enabled us to obtain Best Response Curves for the two Bridges, thus allowing us to determine the equilibrium tolls and traffic flows.

5.3 Major Contribution and Key Findings

This thesis makes a direct contribution to the existing transportation literature on toll competition in the context of cross-border transportation. As noted earlier in the thesis, most of the existing studies on the topic were either theoretical or were applied to conceptual small road networks. To our knowledge, this is the first applied and numerical study that attempted to model toll price competition for the busiest border-crossing region in North America and around the world. The modeling framework we developed provide valuable insights about the nature of the toll competition that will likely emerge in the future should the new Bridge connecting Windsor to Detroit choose to adopt a particular toll strategy. The findings from the numerical analysis provide novel results about the competition equilibrium which allowed us to determine the exact tolls on the two bridges while at the same time simulating the amount of passenger and truck traffic that will utilize the two bridges. Those findings are worth reporting as they could assist the Government of Canada to rationalize the best toll competition strategy in the future.

Three main findings can be drawn from the work reported in this thesis. First, whether the new bridge operator cares about international trade only (trucks only) or cares about both international trade and local traffic (both trucks and passenger cars), it will behave the same. The reason is that the truck VOT is much higher than the passenger car VOT, which makes the passenger car travel time not important from a system economic efficiency perspective. Second, with the new bridge, trucks will probably pay a much lower toll to cross the border due to competition. Thirdly, the more the new bridge cares about the system efficiency, the lower it will set its own truck toll and thereby makes both bridges' tolls lower as a result of competition. The reason is that the new bridge is designed with a very large capacity, which means a higher utilization of the new bridge will improve the system efficiency.

5.4 Limitations and Future Study

The toll competition problem is solved on the basis of fixed demand in this research, which makes the border crossing trip rate constant in all scenarios. This assumption could be relaxed in the future but this would require integrating the developed model of this thesis with a cross-border travel demand model. Additionally, we only considered the duopoly price competition in this study to compare different regimes for the two bridges. However, the model could be expanded to include a larger network which would allow us to account for a third international crossing such as the Blue Water Bridge in Sarnia, Ontario.

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