Dynamic Congestion Pricing in Large Networks: Modelling Approach and a Case Study on the Greater Toronto Area

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Abstract

Congestion pricing is one of the widely contemplated methods to combat traffic congestion. The purpose of congestion pricing is to manage traffic congestion by charging fees (i.e., tolling) for the use of certain roads in order to distribute traffic demand more evenly over time and space. This study presents a framework for large-scale dynamic congestion pricing policy determination and evaluation. The proposed framework integrates departure-time choice and route choice models within a regional dynamic traffic assignment (DTA) simulation environment. The objective is to create a unified dynamic (location- and time-specific) congestion pricing framework that addresses the impact of tolling on: 1) road traffic congestion (supply side), and 2) travellers' behaviour and choice dimensions including departure time and route choices (demand side). The effectiveness of the proposed framework is investigated through a case study on the Greater Toronto Area (GTA). Two tolling scenarios are investigated by using the proposed platform for flat and dynamic tolling. The results indicate that 1) more benefits are gained from dynamic pricing due to departure-time rescheduling as opposed to re-routing, 2) widespread spatial and temporal traffic changes are observed at different locations of the regional network in response to tolling a major, yet relatively short, corridor in the network, and 3) dynamic pricing mirrors temporal congestion patterns and induces departure time re-scheduling while flat tolling causes major and counterproductive rerouting patterns, which may block access to the tolled facility itself.

Introduction

As traffic congestion levels soar to unprecedented levels in dense urban areas, and governments are challenged to meet the demand for transportation and mobility; congestion pricing is becoming one of the widely contemplated methods to combat congestion (1).

The purpose of congestion pricing is to ensure a more rational use of roadway resources. This is accomplished by charging fees for the use of certain roads in order to reduce traffic demand or distribute it more evenly over time (away from the peak) and space (away of congested facilities).

While enumerating all congestion pricing studies is out of the scope of this paper, the following section briefly reviews what is highly relevant to our scope:

In a study conducted at University Drive (Burnaby, BC), single-occupant vehicle (SOV) commuters completed a discrete choice experiment in which they chose between driving alone, carpooling or taking a hypothetical express bus service when choices varied in terms of time and cost attributes. The results of this study indicate that a potential increase in drive alone costs brings greater reductions in SOV demand than an increase in SOV travel time or improvements in the times and costs of alternatives (i.e. carpooling and bus express service) beyond a base level of service (1). Another study conducted at the University of Toronto assessed the potential of congestion pricing against capacity expansions and extensions to public transit as policies to combat traffic congestion. The study concludes that vehicle kilometers travelled (VKT) is quite responsive to price (2). Moreover, Sasic and Habib (3) showed that the recommended strategy to lighten peak period demand while maintaining transit mode share in the Greater Toronto and Hamilton Area (GTHA) requires imposing a toll (around $1) for all auto trips in addition to a 30% flat peak transit fare hike. Furthermore, their results suggest that such a pricing policy would have a larger effect on shifting travel demand over time than any other policies not including a road toll.

Tolling studies in the literature range from applying a flat or simple pricing structure (4, 3) on a small or sometimes hypothetical network (5, 6), to a network-wide pricing scheme (7, 8). Other efforts (9) study dynamic tolling on specific corridors in a micro-simulation environment; in which the network-effect and routing options affected by tolling are not considered. Although these studies contribute considerably to the state-of-the-art and state-of-the-practice in congestion pricing, the literature has some or a combination of the following limitations:

- scarce case studies on realistic and large urban networks;
- hypothetical tolling scenarios that lack methodological/practical basis; and
- disregard of travelers' individual responses to pricing (e.g. choice of departure-time, choice of mode, and choice of route).

In light of the above gaps, this study is motivated to develop a robust framework for the <u>derivation</u> and <u>evaluation</u> of realistic dynamic congestion pricing policies to manage peak period travel demand, while explicitly capturing departure-time and route choices in a large-scale dynamic traffic simulation environment. The functionality/effectiveness of the proposed framework is tested through a case study on the Greater Toronto Area (GTA).

Modelling Framework

With the above objectives in mind, in this section we present a framework for evaluation of dynamic congestion pricing policies as a method of *spatial* and *temporal* traffic management. The proposed framework integrates departure-time choice and route choice within a large-scale dynamic traffic simulation environment.

This section focuses on the following components of the framework: 1) the bottleneck model for dynamic congestion pricing which is the theoretical basis of the dynamic tolling structure adapted in this study; 2) an econometric (behavioral) model of departure-time choices (used in the proposed modelling framework); 3) a dynamic traffic assignment simulation platform (used to enable assessing various pricing options); and 4) finally, the integration and implementation of these modules into the proposed framework.

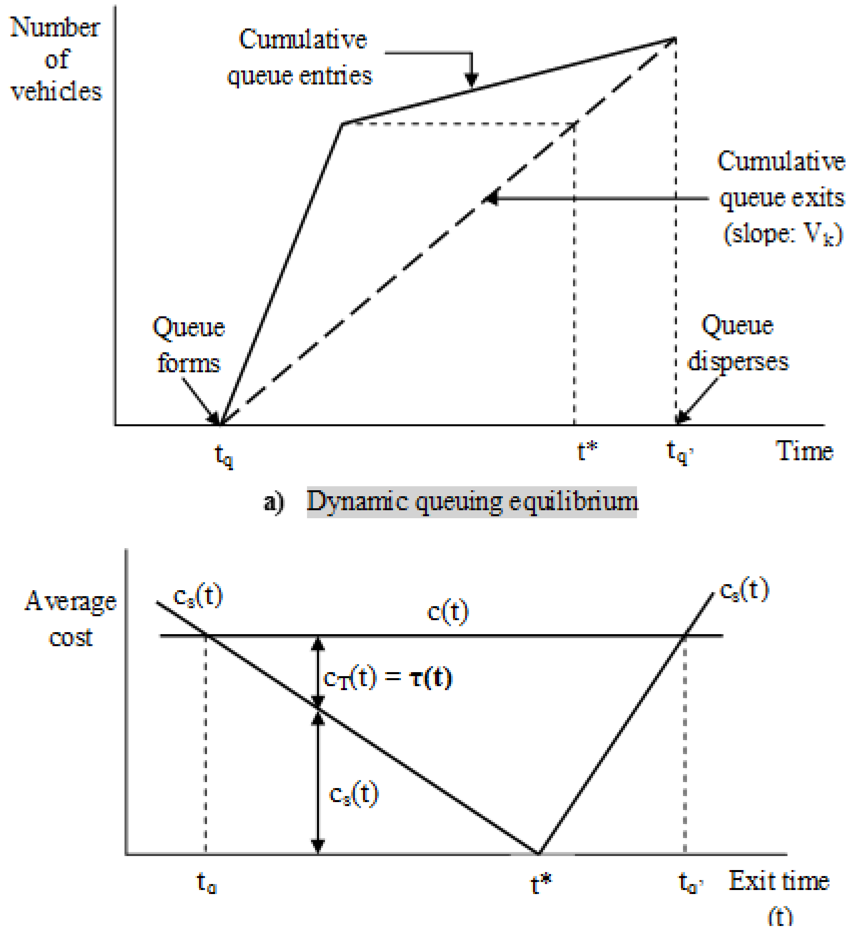
1) Theoretical Basis: The Bottleneck Model for Dynamic Congestion Pricing

Dynamic models consider that congestion peaks over time then subsides. Therefore, there is a congestion delay component that peaks with congestion that the travellers experience. Dynamic models assume that travellers have a desired arrival time t*; deviations from which imply early or late schedule delays. Travellers who must arrive on time during the peak periods encounter the highest delay; i.e., there is a tradeoff between avoiding congestion delay and arriving too early or too late.

The *Bottleneck Model* assumes that for arrival rates of vehicles not exceeding the bottleneck capacity and in absence of a queue, the bottleneck's outflow is equal to its inflow and as a result no congestion (delay) occurs (10). When a queue exists, vehicles exit the queue at a constant rate, which is the same as the bottleneck capacity. Figure 1-a illustrates the un-priced equilibrium condition of this model (i.e., equilibrium in the absence of tolling) and figure 1-b shows the two components of the total cost in the un-priced equilibrium condition, namely, travel delay cost and schedule delay cost (early and late arrival costs).

The optimal toll in this case attempts to “flatten” the peak in order to spread the demand evenly over the same time period. In this case, the price is set such that the inflow equals road capacity, which in turn equals the outflow. Pricing affects the pattern of entries with a triangular toll schedule that replicates the pattern of travel delay costs in the un-priced equilibrium. This toll is shown in figure 1-b as $\tau(t)$. Instead of queuing delay, travellers trade off the amount of toll to be paid or experience schedule delay such that a traveller who arrives right on time t* pays the highest toll.

The toll structure introduced in the current study is inspired from the bottleneck pricing theory; where the benefits come from rescheduling of departure times from the trip origin. The bottleneck model provides a core concept; however, it is very limited to the case of a single bottleneck, where the departure time choice is the only choice travellers have to respond to pricing. In large urban networks, there is a myriad of origin-destination pairs, trip lengths, travellers’ schedules, routing options and travel behavior that vary across the population. Therefore, our pricing framework extends the conceptual triangular pricing structure suggested by the bottleneck model to the more complex case of a large urban network.



b) Average cost components and optimal tolls by queue-exit time

Figure 1: Equilibrium in the Bottleneck Model (10)

2) The Econometric Model for Departure-Time Choice

In order to capture users' individual responses to pricing, this study uses a discrete-choice module to capture the departure-time choice dynamics in response to tolling. It extends a recent research effort conducted at University of Toronto by (3), in which the authors developed a discrete choice model to describe departure-time choice in the GTHA. The developed departure-time choice model is a Heteroskedastic Generalized Extreme Value (Het-GEV) model that further enhances the Choice Set Generation Logit (GenL) captivity component developed by (11).

The Het-GEV model explicitly captures the correlation between adjacent choice alternatives while the GenL form captures the captivity of decision makers to specific choice alternatives due to schedule constraints. The GEV class of models for discrete choice applications makes use of random utility maximization theory, where each agent is assumed to choose an alternative that maximizes its random utility.

Two types of scale parameters are introduced in this model. These are root scale parameter and scale parameter of a particular choice set. Moreover, the modelling framework uses a scale parameterization approach to capture *heteroskedasticity* in departure time choices (3).

Further details related to the model choice set structure, the utility function variables, the model parameters' adjustment process, and the model calibration results are presented later in the paper within the case study on the GTA region.

3) The Mesoscopic Dynamic Traffic Assignment Model

Congestion pricing is typically sought in congested large urban areas, where congestion spreads over space for long peak hours. Therefore, to dynamically control traffic in large-scale congested networks, three systems are needed concurrently: (1) a prescriptive decision-setting/control tool (e.g. a demand or supply control policy such as congestion pricing or ramp metering etc.), (2) a descriptive econometric departure time choice model as discussed above, and (3) a descriptive dynamic traffic assignment model that shall dynamically capture route choice dynamics resulting from travellers seeking the best routes to their destinations. A large scale dynamic traffic assignment simulation model is, hence, required for practical congestion pricing policy derivation and application; a model that can realistically capture the route choice dynamics network-wide resulting from dynamic tolls along key corridors.

For that purpose, a mesoscopic dynamic traffic assignment (DTA) model is used in this study. In general, mesoscopic models simulate the movement of individual vehicles in the transportation network but move them in groups according to the fundamental diagrams of traffic theory. These models offer a compromise between microscopic and macroscopic models; unlike microscopic models, they are less computationally demanding and hence are more suited for modeling large networks (12).

More details related to the demand patterns, which are inputs to the mesoscopic simulation, the key traffic assignment control parameters, and the simulation calibration results will be discussed within a case study on the GTA network in the following sections.

4) The Integrated Dynamic Congestion Pricing Framework

Figure 2 shows the integrated dynamic congestion pricing framework. The ultimate goal of this framework is to provide a tool for dynamic congestion pricing policy derivation and evaluation, while taking into account the route choice and departure-time choice dimensions in large-scale regional networks. The systems works in the following order:

- ***Input Data:*** The system first takes as input the network topology, anticipated demand and user demographics to form a hybrid dynamic traffic assignment and travel behavior model. Moreover, a nonlinear version of the triangular price structure of the bottleneck model is to be provided as input to the system for the facility of interest in the network as shown in the "Dynamic Toll Schedule" module in figure 2.

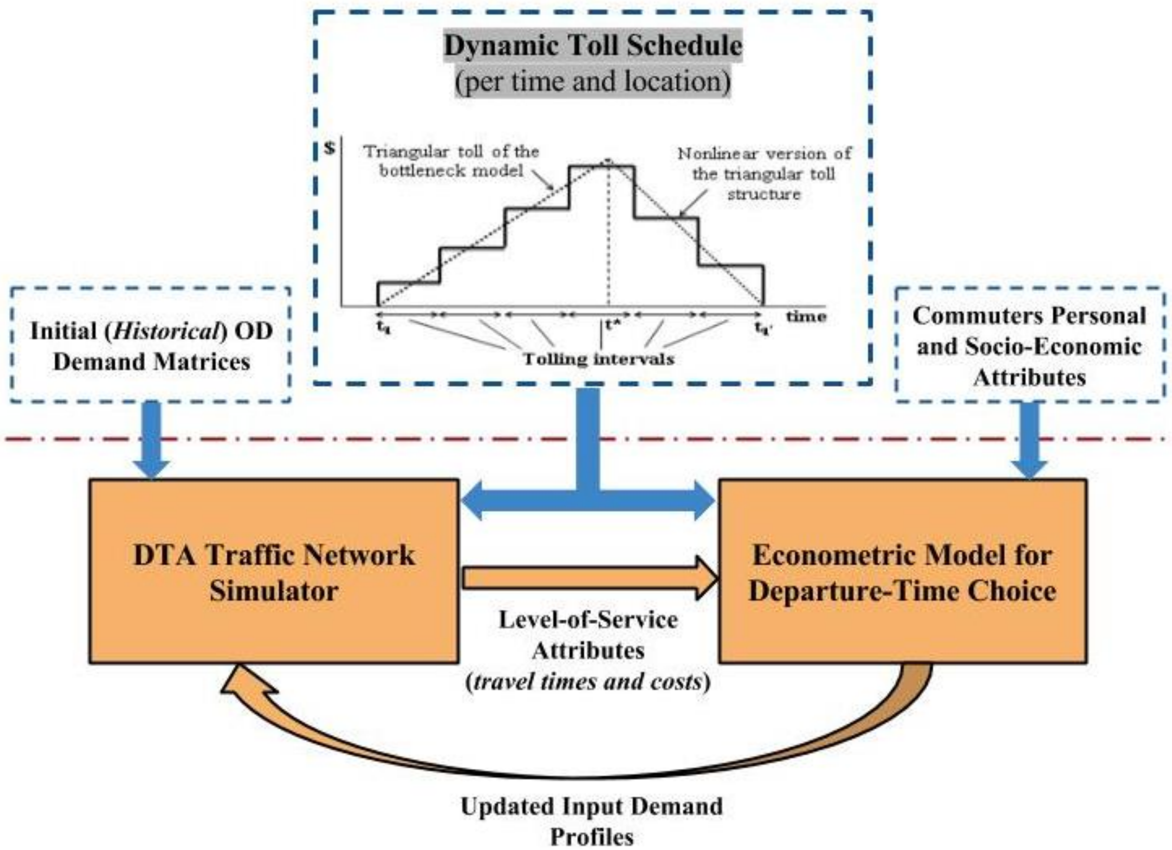


Figure 2: Framework for Dynamic Congestion Pricing Evaluation

- ***Run DTA Simulation Model:*** The DTA simulation model takes the toll structure (which is added to travel costs), and anticipated demand; and performs a dynamic user equilibrium iterative traffic assignment; resulting in OD travel times, updated network conditions, and routing options given the inputs received.
- ***Apply Discrete Choice Model***: The discrete choice model takes as input the toll structure, the socio-economic attributes of impacted drivers, and the average OD travel times and costs calculated across the network from the most recent DTA simulation run. The output of the discrete-choice model represents the *new* temporal demand patterns (with modified start times) due to tolling.
- ***Integrate Departure-Time and Route Choices:*** The equilibrium in drivers' behavioral responses to dynamic pricing policies is sought by **iteratively** and **sequentially** simulating the changes in route choice and departure-time choice in response to tolling

through the DTA simulator and the discrete-choice model, respectively. At the end of each iteration, the discrete-choice module estimates the impact of the input toll schedule given the most recent network conditions (travel times and costs) on travelers' individual departure-time choices. The updated choices are then fed back into the dynamic traffic assignment simulator, which, in turn, produces the new network conditions and so on until certain convergence criterion is met.

An application of the proposed framework on a case study in the GTA is discussed in the next section.

Model Calibration and Application: Case Study on the GTA

Traffic congestion is reaching a crisis level in larger cities and metropolises in Canada and worldwide. The GTA is a vivid example in terms of widespread congestion on all modes, particularly roads. In 2006, the annual cost of congestion to commuters in the GTA was $3.3 billion. Looking ahead to 2031, this cost is expected to rise to $7.8 billion (13).

Different levels of government in Canada are contemplating congestion pricing options to alleviate traffic congestion problems. The Ministry of Transportation Ontario (MTO) is actively evaluating High Occupancy Toll (HOT) lane options (9). In 2013, Metrolinx (an agency of the government of Ontario) released its investment strategy in which it recommended the implementation of HOT lanes as a potential source of fund for transit expansion in the region.

Together these factors strengthen the need to analyze, test, and deploy various traffic control policies (such as the one proposed herein) in order to tackle the alarming congestion problems in the GTA region.

This section presents the implementation details of the proposed framework on the GTA. The section starts with a brief description of the data used in this study, followed by a detailed explanation of the modelling process of the GTA network in DynusT. The last, and main, part of this section corresponds to the departure-time discrete choice model.

1) Data Inputs and Sources

The travel demand related data used in this study is extracted from the 2011 Transportation Tomorrow Survey (TTS) (14). TTS is a household based travel demand survey that is conducted in the GTHA every five years. The survey provides detailed information on trips made on a typical weekday by all individuals in the selected households. Five percent of the GTHA households are contacted by telephone and all trips made by residents eleven years of age or older on a specific weekday are recorded. The 5% sample is then expanded to represent the GTHA population.

2) GTA Dynamic Traffic Assignment Simulation Model

GTA Simulation Model Specification - Network Geometry

The simulation model of the GTA network, used in this study, incorporates all highways, major arterials, on-and-off ramps, as well as traffic signal information at the major signalized intersections in the GTA. The DTA platform used is DynusT (15). As shown in figure 3-a, the network was built to consider arterials and freeways within the GTA to ensure capturing all routing options in response to tolling scenarios, making it one of the largest simulation models built in the region at the mesoscopic level.

GTA Simulation Model Specification - Travel Demand

The time-dependent OD matrices used as input for the GTA simulation model were extracted from the 2011 TTS data survey. The demand extracted was limited to GTA zones, auto mode, and morning trips from 6 to 10:30 am generated every 15 minutes. The majority of home-based work trips in the GTA - on which we focus in this study - were observed to occur during this time interval, according to the findings in (3). Additionally, the background demand (i.e., trips that pass through the GTA network but start and/or end outside of it) was added to the GTA demand. A demand shifting procedure was conducted to capture the time elapsed until those background trips reached the boundaries of GTA network boundary, and then added to the 2011 TTS demand.

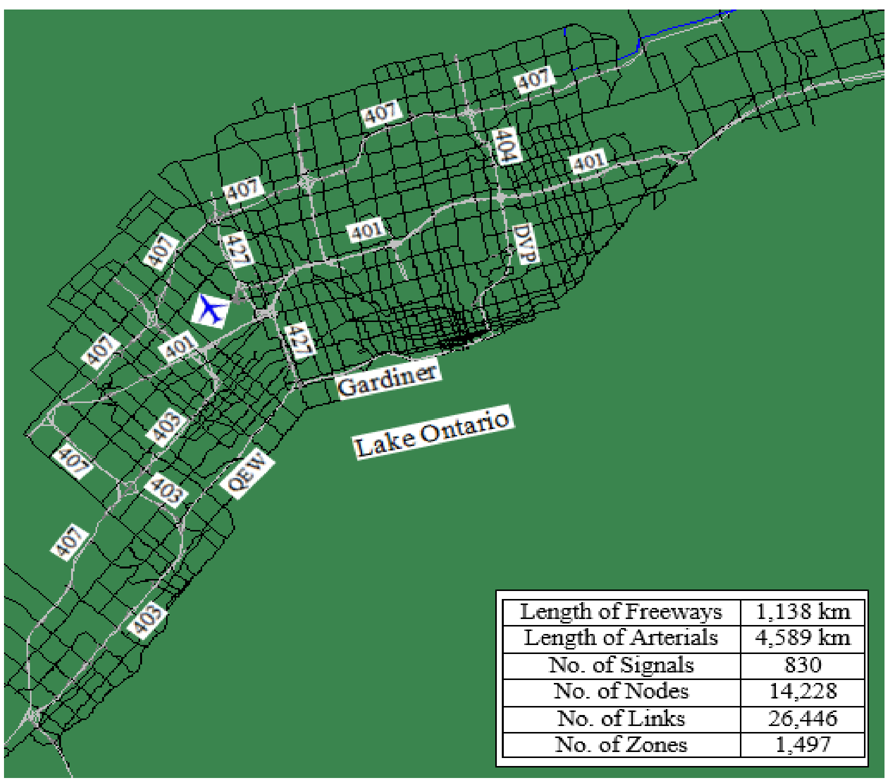
In this study, two types of releasing traffic demand into the network were utilized: 1) typical OD demand matrix, and 2) vehicle-by-vehicle input with detailed start time and path information. Initially, the vehicles in the network are simulated from the existing OD demand matrix; containing multiple time-dependent trip matrices for the simulation horizon, and performed using Dynamic User Equilibrium (UE) assignments. After the convergence of the UE case, and in order to apply the departure-time choice model on specific vehicles to capture the impact of tolling on their start times, the same network is re-simulated with the imposed tolling scenarios using the detailed vehicle-by-vehicle input mode. The latter mode uses (as input) the same vehicles and their associated paths, as identified after the OD demand matrix simulation run.

GTA Network Calibration

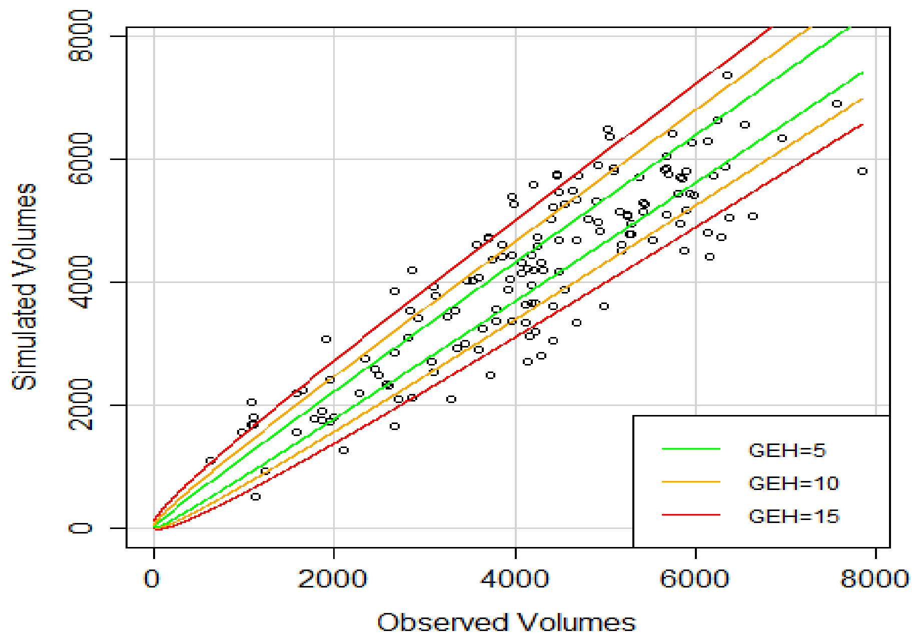
The parameters adjusted in the calibration process of the GTA DynusT simulation network include the two-regime traffic flow model parameters, the freeway bias factor (that controls traveler's perception bias towards freeway travel time), and some network geometry related parameters. The simulated hourly traffic volumes at 177 locations over highways 400, 401, 403, 404, QEW, the Gardiner expressway, and the Lakeshore Blvd were compared against real data collected from loop detectors (16).

The GEH statistic, which is widely used in calibrating traffic simulation models, was used in (16) as an evaluation criterion for the simulated volumes in the GTA simulation model. The GEH statistic is computed as follows:

$GEH = \sqrt{\frac{(V-C)^2}{(V+C)^2}}$, where V is the model estimated hourly volume at a location and C is the hourly count at the same location. The average GEH of the whole model is **<u>9.75,</u>** as shown in figure 3-b. In this study, the average value of time (VOT) used in the simulation model for the GTA is $**<u>15/Hr.</u>**, according to (17) and after applying the conversion rate to 2011 Canadian dollars.



a) Snapshot of the GTA DynusT Simulation Model



b) Scatter Plot of the Observed and Simulated Hourly Volumes (16)

Figure 3: GTA Network Related Information

3) Econometric Model for Departure-Time Choice in the GTA

This section describes the details of the econometric model used in this study to model the departure-time choice in the proposed dynamic congestion pricing framework. The section starts with an introduction to the model choice set formulation, followed by a discussion of the original variables used in the utility functions as well as the extensions and assumptions done to incorporate schedule delay and toll cost components in the model variables. Lastly, the re-calibration process of some model parameters and the final validation results are presented.

Model Formulation

The model was originally developed by (3) for the departure time choices of home-based commuting (home to work or school) trips in the GTHA. The datasets from the 2006 TTS survey (14) were used for empirical model estimation.

In this model, departure-time is represented as nine discrete time intervals that span the morning peak, when the majority of home-based work trips occur. The choice framework resembles the decision making process where an individual chooses his/her departure time within a specific range (portion) of the day. In other words, the probability that an individual chooses to depart from home to work during some interval is defined as the weighted sum of the probability of choosing this time interval over the one preceding it and the probability of choosing this time interval over the one following it.

Model Variables

Two types of explanatory variables exist, in this model: 1) commuters' personal and socio-economic attributes; and 2) transportation level-of-service (LOS) attributes corresponding to alternative departure time segments. Commuter attributes include: work duration, occupation category (general office, manufacturing, or professional), gender, job status (full-or-part- time), and age category. LOS attributes involve travel time, travel distance, and travel cost corresponding to each departure-time segment.

To prepare the data required for applying the model on the GTA, commuters' attributes of all morning (6 to 10:30 am) auto commuting trips - reported in the TTS 2011 dataset - were linked to the corresponding trip LOS attributes generated by the DTA DynusT simulation model of the GTA.

It is important to note that the model above does not include an *explicit* variable for the toll cost as the TTS survey dataset contains no toll information to assist in the coefficient estimation of such parameter. For the sake of dynamic pricing policy testing in this study, the imposed tolls are added to the travel cost variable.

Although the schedule delay cost is intuitively an important factor contributing to the departure-time choice for morning commuting trips (having specific desired arrival time), this variable is absent from this model since the work/school start times of commuting trips are not reported in the TTS survey. The schedule delay cost is, however, crucial to attain the anticipated departure-time rescheduling benefits of the bottleneck triangular pricing adapted in this study. Accordingly, this variable is added to the travel time variable. The detailed formula used in this study for schedule delay as well as the determination process of its parameters are presented in the next sub-section.

Empirical Model of Departure-Time Choice

As mentioned before, the empirical model was estimated based on the datasets from the 2006 TTS survey. The alternative specific constants (ASCs) were hence updated to be consistent with the 2011 dataset, according to the following rule (18):

$$\boldsymbol{ASC_{i_{New}} = ASC_{i_{Original}} + ln(\frac{A_i}{S_i}), i = 1, 2, 3, ..9}$$

Where A_i is the share of decision-makers in the 2011 population who chose departure-time interval i; whereas S_i is the share of decision-makers in the 2006 population who chose alternative i.

The schedule delay cost, c_s, used in this study takes the following formula (19):

$$c_s = \begin{cases} \beta(t_d - t - T(t)) & if\ t + T(t) \leq t_d \quad (Early\ Arrival\ Cost) \\ \gamma(t + T(t) - t_d) & if\ t + T(t) > t_d \quad (Late\ Arrival\ Cost) \end{cases}$$

where β and γ are the shadow prices of early and late arrival delays, respectively. t is the trip start time, $T(t)$ is the travel time, and t_d is the desired arrival time. As mentioned before, the commuters' desired arrival time info is not reported in the TTS survey. Accordingly, this variable was randomly generated for each vehicle in the network (once at the beginning of the simulation) following a Log-Normal distribution. Several values were tested for the mean and standard deviation of this distribution; 8:30 am was ultimately selected as the mean desired arrival time and 0.05 was set as the standard deviation. These selected values entail the best relationship between travel time and schedule delay cost values; such that the minimum schedule delay costs are observed at the same time interval where the maximum travel time delays are experienced, and vice versa, as suggested by the bottleneck model (figure 1-b).

According to (19), the early and late arrival delays are perceived differently by commuters and hence have different coefficients (i.e., shadow prices) in the schedule delay cost function with a ratio of 1 to 4, respectively. This ratio was further modified in this study, during model validation, to be 1 to 2.

Now that the schedule delay cost is added to the travel time, the coefficients of travel time in the utility functions needed to be recalibrated. The calibrated parameters were determined using a *factorial design* procedure (20). The objective of this procedure was to determine the set of parameters that minimize the absolute error between the observed and the estimated values at all time-intervals; for the following measurements:

- number of commuters who chose to depart at each time interval;
- average resulting travel time per km; and
- average travel distance travelled.

Figure 4 shows comparisons between observed and estimated/simulated measurements, when applying the calibrated discrete choice model iteratively with the DTA simulation model in the base case (i.e., without tolling). The patterns shown in the figure indicate the best attainable correspondence between the observed measurements and their corresponding simulated values. The findings from figure 4 demonstrate the robustness of the implemented/calibrated framework when applied on the GTA in the base case.

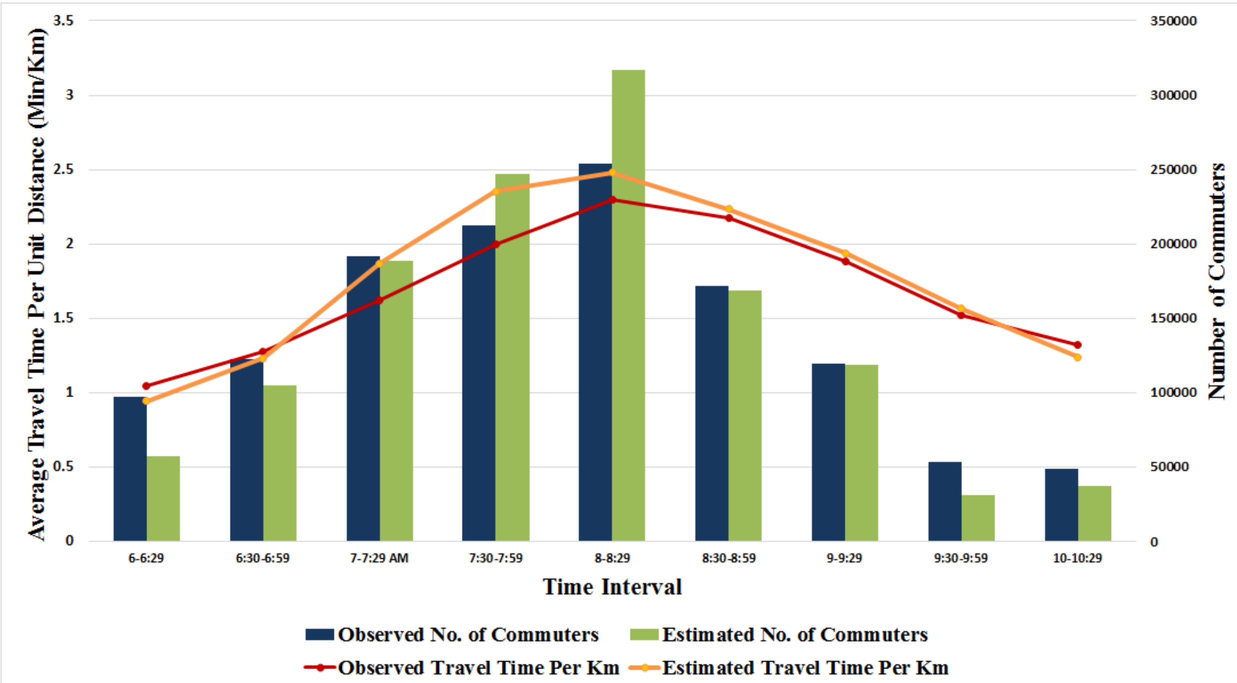


Figure 4: Comparisons between Observed and Estimated Simulation Measurements

The discrete choice model has 74 statistically significant parameters, among which only 18 were needed to adjust as per validation of the model outputs; for the following reasons: 1) to update the model to be consistent with the 2011 TTS dataset being used, and 2) to adapt with the added schedule component cost. The retrofitting process performed, however, shouldn't affect the robustness of the original model formulation given its relatively large number of parameters and statistically significant explanatory variables, as well as the parameterized root and nested scale parameters.

In the following section, the application of the overall dynamic congestion pricing framework is illustrated using tolling scenarios in the GTA.

Tolling Scenario Evaluation

1) Tolled Route (Gardiner Expressway- GE)

The Gardiner Expressway (18 km, six-to-ten lanes wide, between Highway 427 and the Don Valley Parkway (DVP)), as shown in figure 3-a, is the main artery running through Downtown Toronto and connecting it with its western suburbs. In addition to the fact that the GE suffers from extended periods of congestion, there is an ongoing debate on whether to tear it down, to toll it and use the revenue for its maintenance, or to apply other hybrid proposals to improve its operation. Hence, the GE was selected as the testbed for this study to study the effectiveness of the proposed dynamic congestion pricing framework. It is important, however, to mention that although the pricing strategy is applied only on this main artery within the heart of Toronto, the simulations and analysis are conducted on the entire GTA network, due to the inter-connectivity and multiple routing options existing in this network and to capture regional effects.

2) Toll Structure

The toll considered is distance-based and its value is entered in $/km. Additionally, the same toll value is imposed, at each time interval, on all GE links in both directions (eastbound and westbound) for practicality and clarity to drivers. However, different toll values are set at different time intervals, according to a triangular structure (as shown in figure 2), i.e., the toll structure - in this study - is assumed to be flat over space but variable over time. The dynamic-tolling intervals used are the same nine *half-hour* intervals, for compatibility with the departure-time choice model.

Determination of Morning Peak Period Duration and Dynamic Toll Structure

The number of daily trips made - during the morning period considered - on the GE corridor (i.e., the Gardiner Expressway and its parallel arterials) is approximately 90,000. In order to attain the departure-time scheduling benefits of dynamic tolling, the toll pattern should replicate the queuing delay pattern during the peak period, as suggested by the bottleneck model. For that purpose, the toll structure determination process starts with determining the morning peak period start and end times (on the GE corridor) as well as the pattern of excess travel time (i.e., queueing delay) during that period.

As shown in figure 1-a, the peak period starts when the demand exceeds the available route capacity, resulting in traffic queues that build-up to a maximum when the demand starts decreasing below capacity. The peak does not end at this point of time; rather, it ends when all travellers who entered the system (from the beginning of the peak period) ultimately exit after being queued for a while.

According to this definition, and based on the demand information and the - base case - simulation results of the trips made on the GE corridor; the peak period start and end times were found to be 7 am and 9:30 am, respectively. Consequently, no toll is imposed before 7 am nor after 9:30 am in the dynamic pricing scenarios tested in this study. Additionally, the toll pattern selected is proportional to the pattern of queueing delays on the corridor between 7 am and 9:30 am.

Tolling Scenarios

In order to study the effectiveness of the proposed framework in dynamic congestion-pricing policy evaluation, two tolling scenarios are investigated: 1) dynamic tolling structure, and 2) flat tolling across all time intervals; its value was set by taking the average of the time-dependent toll values of the first tolling scenario as shown in figure 6-a.

3) Results and Conclusions

Network-Wide Analysis

Figure 5 shows the major routing decision points for traffic approaching Toronto. The results are summarized in the form of <u>percentage difference</u> of overall traffic flow during the morning peak period along the key corridors between the base case, the flat tolling and the dynamic tolling scenarios. Examining the results indicate the following:

<u>Dynamic Tolling</u>

- Overall, the dynamic toll resulted in mild routing options across the GTA when compared to the flat tolling scenario; -1% at QEW, -3% at Highway 427, +3% at Highway 401, and -4% at DVP.
- At the GE, only 5% divergence was observed at the bifurcation to Lake Shore; resulting in maximizing the efficiency of the downstream sections of the GE.

<u>Flat Tolling</u>

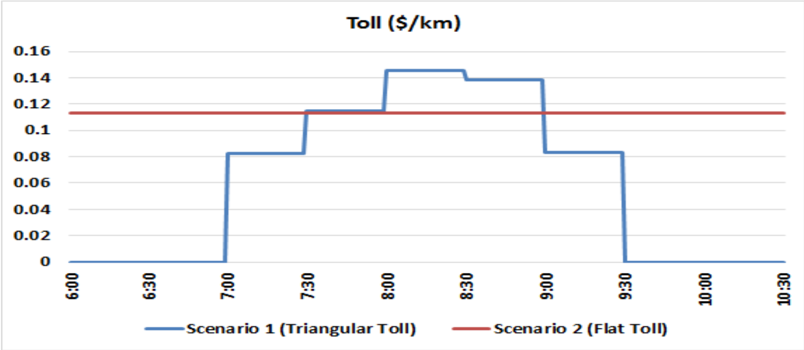
- Overall, the flat toll resulted in more obvious re-routing patterns across the GTA compared to dynamic tolling; showing -2% at QEW, -7% at Highway 427, +5% at Highway 401, and -5% at DVP.
- At the GE, significant divergence was observed at the bifurcation to Lake Shore; resulting in shockwave and congestion upstream of this bifurcation. This congestion resulted in – interestingly – less volume on the GE downstream the off-ramp to Lake Shore, i.e., underutilizing the GE by as much as 43%. This observation was confirmed by the low speed values (20-28 km/Hr.) along these sections of the GE.

Figure 5: Major Routing Decision Points for GE Corridor Traffic and the Average Travel Time on the GE Eastbound (from 427 to DVP)

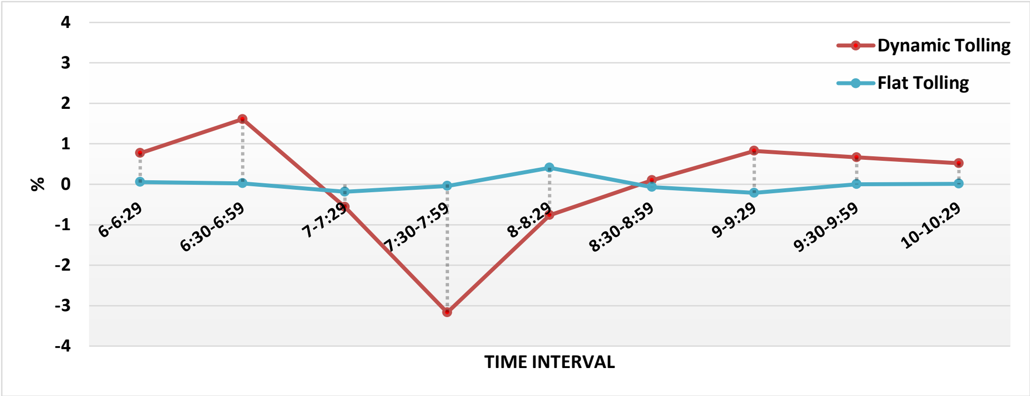
Trip-Based Analysis

Figure 6 shows the changes in departure-time choices and travel times of the 90,000 trips made on the GE corridor in the morning period, at different tolling scenarios. This analysis involves <u>all the trips</u> that are affected by tolling the GE, including:

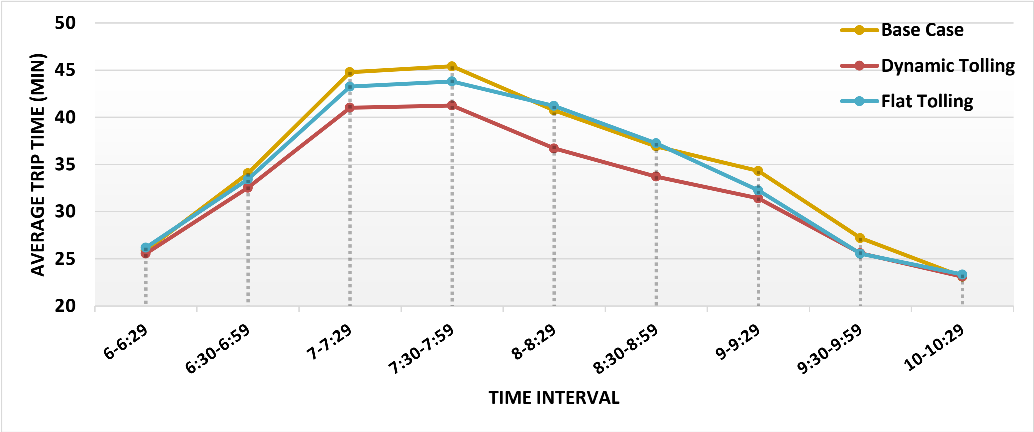
- trips passing through the tolled route;
- trips diverting from the tolled route to other parallel arterials after tolling (e.g. the Lake Shore Blvd); and
- trips on the parallel arterials that might be affected by the route shifts out of the tolled route.



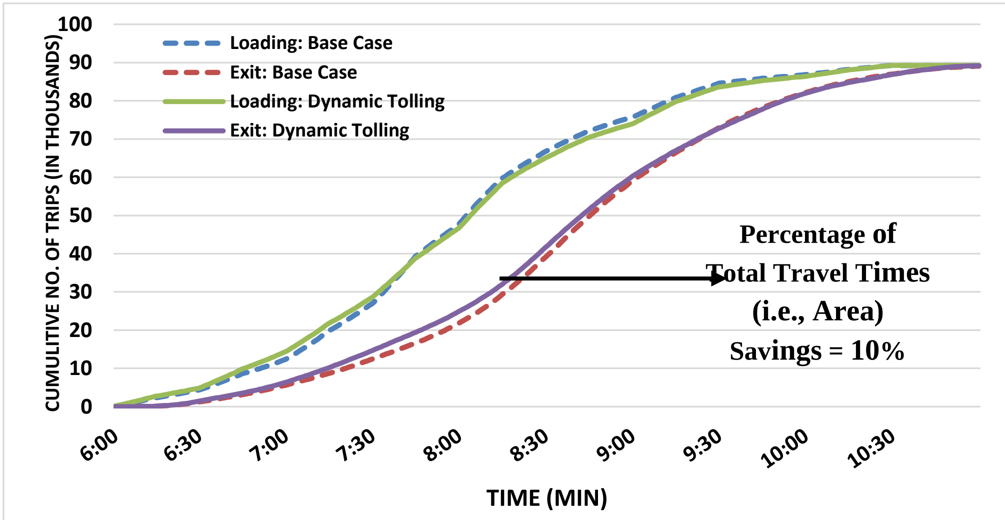
a) Tolling Scenarios 1 and 2 for the Gardiner Expressway



b) The Percentage of Trips Shifted (from or to) Each Time Interval



c) Average Travel Time among Trips Started at Each Time Interval



d) Loading and Exit Curves of the GE Corridor after Dynamic Tolling

Figure 6: Analysis of GE Corridor Trips at Different Tolling Scenarios

<u>Dynamic Tolling</u>

As clear from figure 6-b, dynamic tolling entails shifting around 5% of the peak hour corridor traffic (from 7:30 am to 8:30 am) to earlier and later time intervals. As a result, lower travel times are observed at all time-intervals after dynamic tolling, as in figure 6-c. Examining the results reported in this figure, for the dynamic pricing scenario, shows that 10% savings in the total travel times of the corridor users (at all time-intervals) were attained, relative to the base case. Additionally, the 8 to 8:30 am time interval contributed the most to those savings. This is also noticed in figure 6-d; the total area between the GE corridor loading and exit curves (which represents the total travel times spent on the GE and its parallel arterials) shrunk by 10%. The benefits come from rescheduling of departure times from the trip origin, in addition to the route shift impacts of tolling.

<u>Flat Tolling</u>

Flat tolls, as expected, create no incentive for drivers to change their departure-times. This is noticed in figure 6-b. This scenario outperforms the base case by 2% net savings in the total travel times. The benefits, in this case, come *solely* from the route shift impacts of tolling. However, as clear in figure 6-c, this gain is realized more at early and late intervals while some deterioration in travel times is observed at peak time intervals (8 to 9 am). Further explanation for these findings will be given in the corridor-based analysis.

Corridor-Based Analysis

Figure 5 shows the average travel times on the tolled route (the GE), eastbound direction, from highway 427 to the DVP for different tolling scenarios.

Dynamic Tolling

As noticed in figure 5, dynamic tolling entails noticeable decrease in travel times on the tolled route; especially at the middle congested time intervals. The maximum saving observed is 7 min (out of 27 min), i.e. around 25 %, at the 8 to 8:30 am time interval.

Flat Tolling

Flat tolling results in improvements in travel times at early and late intervals. However, it causes significant increase in travel times on the tolled route from 8:30 to 9:30 am, as clear in figure 5. The deterioration occurs due to the excessive demand at peak hours that didn't shift to other time intervals due to absence of incentive (i.e., no toll variation over time). This demand tries to exit the tolled route (the GE) to the immediate parallel arterials (Lake Shore Blvd) and is limited by off-ramps and downstream capacity constraints. Therefore, it creates a shockwave/congestion upstream that blocks the tolled route itself at peak hours.

Conclusions and Future Work

Congestion pricing is widely viewed among economists and practitioners as one of the promising control tools to tackle traffic congestion. Significant body of research has been conducted thus far in this area. However, case studies on realistic and large urban networks are scarce. Additionally, the tolling scenarios applied in most practical-oriented studies lack methodological justification. Furthermore, the users' individual responses to pricing (e.g. departure-time) were usually disregarded. In this study, a framework for dynamic congestion pricing policy evaluation has been presented with detailed implementation information on a case study in the GTA. The framework involves a discrete-choice model for departure-time choice that has been extended in this study to incorporate a schedule delay cost component for realistic modeling of morning peak travel behavior. The framework has been utilized to analyze the impact of different tolling scenarios.

It can be concluded from the analysis of different tolling scenarios presented in this study (on network, trip, and corridor basis) that:

1. In a large-scale interconnected network (like the GTA), tolling a relatively short, yet major, highway (like the GE) creates temporal and spatial traffic changes network-wide that go beyond the tolling interval and the tolled corridor. This confirms the necessity of

conducting the simulations on a large-scale simulation environment for realistic policy *determination* and *assessment*.

2. More benefits are gained from departure-time re-scheduling due to dynamic pricing, compared to just re-routing as in flat tolling. This emphasizes the importance of the integrated discrete-choice module to the proposed dynamic congestion pricing framework, to provide a realistic modeling of users' individual departure-time responses to dynamic pricing policies.
3. Pricing that induces re-routing only (and no departure time re-scheduling), or excessive re-routing due to, for instance, over pricing, can send traffic to off ramps to parallel routes so aggressively that it blocks the main freeway and the subsequent priced road itself. This emphasizes the importance of dynamic pricing to mirror congestion patterns over time, which is the methodological basis (adapted from the bottleneck model) of the proposed dynamic tolling framework.

The next step in this research is to integrate an optimization module to the dynamic congestion pricing framework that solves for the optimal toll structure (i.e. toll value on each tolled link for every time interval) producing the optimal schedule of entering the system and spatial distribution of traffic across the network that would minimize the total travel delay and maximize infrastructure utilization.

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