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Time-dependent congestion pricing system for large networks: Integrating departure time choice, dynamic traffic assignment and regional travel surveys in the Greater Toronto Area

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ABSTRACT

Congestion pricing is one of the widely contemplated methods to manage traffic congestion. The purpose of congestion pricing is to manage traffic demand generation and supply allocation 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 variable 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 framework addresses the impact of tolling on: (1) road traffic congestion (supply side), and (2) travelers' choice dimensions including departure time and route choices (demand side). The framework is applied to a simulation-based case study of tolling a major freeway in Toronto while capturing the regional effects across the Greater Toronto Area (GTA). The models are developed and calibrated using regional household travel survey data that reflect the heterogeneity of travelers' attributes. The DTA model is calibrated using actual traffic counts from the Ontario Ministry of Transportation and the City of Toronto. The case study examined two tolling scenarios: flat and variable tolling. The results indicate that: (1) more benefits are attained from variable pricing, that mirrors temporal congestion patterns, due to departure time rescheduling as opposed to predominantly re-routing only in the case of flat tolling, (2) widespread spatial and temporal re-distributions of traffic demand are observed across the regional network in response to tolling a significant, yet relatively short, expressway serving Downtown Toronto, and (3) flat tolling causes major and counterproductive rerouting patterns during peak hours, which was observed to block access to the tolled facility itself.

1. Introduction and background

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 (Washbrook et al., 2006).

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The "tragedy of the commons" concept has been established longer than a century ago as mentioned by Hardin (1968). A famous example is when herders are given free access to open grassland for their cows to graze, cows tend to overgraze and deplete their source of sustenance to the detriment of everyone. The parallel to the tragedy of the commons in traffic could not be more direct. While transportation authority and society at large would like to "optimize" travel and minimize overall cost of travel, travelers act very differently. Travelers act independently and rationally, based on their self-interest, i.e., minimizing their direct cost while not paying attention to the societal cost and the detriment to others. Consequently, the purpose of congestion pricing is to manage traffic demand generation and supply allocation to ensure a more rational use of roadway networks. 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 period) and space (away from overly congested facilities).

Numerous studies have investigated the potential of congestion pricing schemes in reducing the vehicular demand subject to travel and behavioral characteristics. While fully enumerating all congestion pricing studies is beyond the scope of this paper, the following section briefly reviews what is highly relevant to our scope:

In a study conducted by Washbrook et al. (2006) at University Drive (Burnaby, British Columbia), 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). Another study conducted by Duranton and Turner (2011) 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 traveled (VKT) is quite responsive to price as opposed to transit or capacity expansions. Moreover, Sasic and Habib (2013) 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, e.g., Lightstone (2011) and Sasic and Habib (2013), on a small or sometimes hypothetical network, e.g., Gragera and Sauri (2012) and Guo and Yang (2012), to a network-wide pricing scheme, e.g., Verhoef (2002) and Morgul and Ozbay (2010). Finkleman et al. (2011) studied the acceptability and impacts of HOT lanes in the GTA through a stated preference survey of more than 250 drivers, under various trip conditions and for various traveler characteristics. Other efforts, e.g., Nikolic et al. (2015), studied dynamic tolling of HOV lanes on specific corridors in a micro-simulation environment; in which the network-effect and routing options affected by tolling were not considered. Mahmassani et al. (2005), Lu et al. (2006, 2008), Lu and Mahmassani (2008), and Lu and Mahmassani (2011) developed a multi-criterion route and departure time user equilibrium model for use with dynamic traffic assignment applications to networks with variable toll pricing. The model considers heterogeneous users with different values of time, values of (early or late) schedule delay, and preferred arrival time (PAT) in their choice of departure times and paths characterized by travel time, out-of-pocket cost, and schedule delay cost. Furthermore, the model was applied to an actual relatively small network (180 nodes, 445 links, and 13 zones) through a simulation-based algorithm. The authors, however, acknowledge that their algorithm suffers from computational limitations in a large network setting.

All these studies contribute considerably to the state-of-the-art and state-of-the-practice in congestion pricing; nevertheless, the literature has some or a combination of the following limitations:

- scarce case studies on large-scale realistic regional networks/models (as opposed to hypothetical small 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). Additionally, the limited number of studies that considered some of those responses ignored the drivers' personal and socioeconomic attributes affecting the decision made in response to pricing, perhaps due to lack of large scale travel surveys.

In light of the aforementioned gaps, this study is motivated to develop a robust framework for the methodological derivation and evaluation of variable 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 study, through rich travel survey data available in the Greater Toronto Area (GTA), considers the drivers' heterogeneity in their values of (early or late) schedule delay and desired arrival times. Moreover, drivers' personal and socio-economic attributes – affecting the choice of departure times – are taken into account besides the trip-related travel time, out-of-pocket cost, and schedule delay cost. The DTA model is calibrated using actual traffic counts from the Ontario Ministry of Transportation and the City of Toronto. The framework addresses the impact of tolling on: (1) road traffic congestion (supply side), and (2) travelers' choice dimensions including departure time and route choices (demand side). Mode choice responses to tolling are beyond the focus of this study and will be considered in future work. The framework is applied to a simulation-based case study of tolling a major freeway in Toronto (the Gardiner Expressway) while capturing the regional effects across the GTA, in Ontario, Canada. The case study examined two tolling scenarios: flat and variable tolling.