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Incorporating departure time choice into high-occupancy/toll (HOT) algorithm evaluation

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Abstract

This paper presents an evaluation framework for high-occupancy/toll (HOT) lanes, extending previous frameworks by incorporating departure time choice alongside stochasticity in demand. Drivers are divided into two classes, strategic and captive drivers. Strategic drivers time their departures to minimize expected generalized cost and can choose either the free lanes or HOT lane. Captive drivers have random departure times, and must choose the free lanes. Generalized cost for strategic drivers takes the form of the well-known schedule delay penalty function combined with travel time. The traffic flow model involves two parallel bottlenecks, one for each lane group. Four toll algorithms are compared: a fixed toll which is constant in time and unresponsive; a dynamic, but unresponsive toll based on expected demand; a dynamic and responsive toll which adapts based on congestion in the HOT lane; and a "full-information" toll which is aware of all captive driver inflows.

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1. Introduction

High-occupancy/toll (HOT) lanes attempt to manage congestion by permitting low-occupancy vehicles to use a designated lane or set of lanes by paying a toll, while high-occupancy vehicles can use these lanes for free. HOT lanes are parallel to a toll-free set of general purpose (GP) lanes. Typically, this toll is dynamic, responding to the congestion level, time of day, and other factors. Designing dynamic pricing algorithms is nontrivial. Several objectives can plausibly be considered. More importantly, there are many factors influencing the choices of drivers and the performance of the facility. Understanding and addressing the various factors is a critical challenge, not yet fully addressed in the literature.

In this paper we use an equilibrium evaluation framework, as it offers tractability and thus insights into the underlying processes. In the current framework, two types of choices are modeled. First, each driver must choose a departure time; second, upon arriving at the split between the GP and HOT lanes, drivers must choose which lane to take. The departure time decision is habitual, and this paper assumes that drivers departure times are the same each day and do

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not depend on specific travel conditions on that day. We assume that drivers are provided information on the current toll and travel times on GP and HOT lanes right before making the lane choice decision. This decision is "real-time" rather than habitual, and can vary from one day to the next based on current travel conditions, which in our model are stochastic.

This paper follows most directly from Gardner et al. (2013) and Gardner et al. (2015), which are discussed here; relationships with other HOT lane literature are described in the literature review. Gardner et al. (2013) focused on alternative choice models for HOT lane choice, and compared three simple algorithms. Under the relatively simple assumptions in that paper, the principle of "full utilization" works well, in which the number of vehicles entering the HOT lane is maximized subject to a capacity constraint. When there is uncertainty in demand, however, it is not generally possible to achieve full utilization at all times, but algorithms based on this principle still seem to perform well. Gardner et al. (2015) made such a comparison while introducing stochasticity in arrival rates. Both papers demonstrate the advantages of equilibrium frameworks.

However, both of these papers assume that the arrival time profile of vehicles is fixed and independent of the toll algorithm. In reality, drivers may adjust their departure times based on the toll algorithm and HOT lane performance, particularly if it offers a more reliable travel alternative. The objective of this paper is to incorporate departure time choice effects into the HOT evaluation framework of Gardner et al. (2013) and Gardner et al. (2015).

We use a fairly standard departure time choice model, in which the generalized cost is a linear combination of travel time, early arrival penalty and late arrival penalty. However, equilibrium models of departure time choice usually do not include stochasticity, which is essential for the evaluation of HOT facilities. Therefore, the key challenge is how to integrate departure time choice and stochasticity. This can be done in many different ways, reflecting additional complexities of the reality. Our goal is to find a relatively simple integrated scenario, leading to a tractable model, which can be useful for the understanding of the primary effects of departure time choice on HOT facility performance. The novelty of this paper stems from the proposed scenario/model.

In reality, typically, all drivers choose their departure time, all drivers can choose whether to use the HOT lane or not, and the moment of arrival to the HOT lane entrance has a stochastic component for all drivers. Representing this complete mixture in an equilibrium framework can be very challenging, and to the best of our understanding does not lead to a tractable model. Therefore, we decided to separate drivers into two classes: strategic and captive. This framework is used to compare the performance of several toll algorithms, and evaluate HOT alternatives against an alternative where all lanes are free. Strategic drivers are further distinguished by their heterogeneous value of time (VOT). They choose their departure times based on the schedule delay concept. They also choose whether to use the HOT lane or not. Their travel time from departure to the HOT lane entrance is assumed constant. Captive drivers always use the GP lane. Their departure rate has a pre-specified time-dependent expected value, while actual departures can be stochastic or deterministic. Their role is to introduce day-to-day stochasticity of GP queue length, and thus travel times. The proposed separation lead to a tractable equilibrium model, described in detail in section 3, that incorporates departure time choice, HOT lane choice, and stochasticity. It can therefore serve as a useful tool for studying the effects of departure time choices in the context of HOT facilities.

In this paper we used the proposed framework to compare the performance of several toll algorithms, and evaluate HOT alternatives against an alternative where all lanes are free. In particular, four toll algorithms are compared. Two are relatively extreme cases which aim to serve as performance bounds: a time-invariant, unresponsive toll (which may nevertheless be set at an arbitrary value), and a "perfect-information" toll which can achieve full utilization by having complete information on departure rates and the stochastic realization. The other two are considered more realistic: an unresponsive, but time-varying toll which would achieve full utilization at mean demand rates, and a responsive toll which adjusts the latter based on current occupancy in the HOT lane. These are demonstrated on a test facility similar to that in Gardner et al. (2013) and Gardner et al. (2015) to facilitate comparison and identify the impact of departure time choice modeling.

The remainder of the paper is organized as follows. Section 2 discusses past literature on HOT lanes, particularly toll algorithms and evaluation methods, and also reviews departure time choice models. Section 3 presents the model components, including the facility and traffic flow, strategic and captive drivers, toll algorithms, and the equilibrium concept used. Section 4 discusses the heuristic devised for the equilibrium model and discusses other implementation details. Section 5 presents the case study and results, and Section 6 concludes and identifies future research directions.