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Introducing and testing a game-theoretic model for a lottery-based metering system in Minneapolis, United States☆

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A B S T R A C T

This paper is part of an ongoing research that analyzes the feasibility of implementing "buyout" auctions for metering traffic inflow at special use lanes (such as high-occupancy/toll lanes). The term "buyout" refers to the fact that these games allow skipping the auction by paying a price. The ongoing research suggests that high consideration needs to be put on the road design before developing a game-theoretic model. It also suggests that from an operations point of view, if a "buyout lottery" system can be implemented successfully, then its conversion to a buyout auction system becomes straightforward. Therefore, this paper aims at: (1) testing a buyout lottery-based metering (LBM) system in a real case scenario, and (2) introducing a game-theoretic model that recommends to its users the strategy to adopt when deciding between paying the toll or playing the lottery.

This paper introduces a microsimulation model of an LBM system that is applied to the city of Minneapolis. This model is then used to evaluate the system's congestion and revenue effects, always assuming that drivers adopt what is referred as the "safest strategy". In the evaluation, a set of most likely lottery scenarios is also obtained. Finally, a game-theoretic model is introduced for obtaining the best strategy. This strategy is compared with the safest strategy, in the context of the most likely lottery scenarios.

The results from the microsimulation model suggest that the LBM system reduces congestion significantly and increases revenue. The best strategy obtained from the game-theoretic model presents challenges for its calculation. But in the context of the most likely scenarios, this paper suggests that drivers should adopt the safest strategy. The safest strategy may coincide with what are commonly known as "minimax regret" and "maximin" strategies.

1. Introduction

High-occupancy vehicle (HOV) lanes, high-occupancy/toll (HOT) lanes, and dedicated bus lanes restrict their use to vehicles that meet certain conditions. This paper refers to these types of lanes as "special use" lanes. As a result of the restriction, not all the capacity is used but just a fraction. This fraction becomes the new threshold that special use lanes are not supposed to exceed, and it is referred in this paper as managed capacity. Exceeding this threshold would harm the good level of service that special use lanes are supposed to offer. But, while using more managed capacity than what is available is undesirable, not using it in its entirety can also be undesirable. HOT lanes for example, are sometimes expected to use the entirety of their managed capacity so that the most number of vehicles can be taken away from the more congested adjacent lanes, commonly known as general purpose (GP) lanes. Olarte and Haghani (2013) argued through an example (but not proved) that special use lanes are not capable of using the managed capacity in its entirety, leaving in this way unused gaps. This paper refers to those gaps as "unused managed capacity". Even HOT lanes, which have a price-based metering system, can have significant unused managed capacity.

This paper proposes a lottery-based metering (LBM) system. The system regulates the traffic inflow that enters the HOT lane (and by extension other types of special use lanes) thanks to the implementation of a "buyout lottery". A buyout lottery is a mechanism in which single occupant vehicles can enter the HOT lane if they choose to pay the toll price. But they can also choose to participate in a lottery. During the lottery, the operator makes a random selection among the drivers who chose to participate within the same short time interval. If a participant wins, then she can detour to the HOT lane. Otherwise,

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that participant keeps driving to the GP lanes. It may be established that winners of the lottery pay a “reserve price”, that is, an amount lower than the toll price once they win. Participants in the lottery compete for several available entrance slots (or lottery items). Ideally, the number of lottery slots (or to be more precise, the number of slots of several lotteries) should be equal to the unused managed capacity because such is the main goal of the LBM system: to eliminate unused managed capacity.

The aforementioned goal benefits the public operator who seeks to mitigate traffic congestion. In addition, two other goals could also be achieved as explained here. Today, HOT lanes offer a reliable trip to its users. Studies have shown that reliability is one of the main factors that attract HOT-lane users (Goodall and Smith, 2010; Liu et al., 2011). But perhaps there is another market that arises whenever there are trip purposes that do not need as much reliability. Such is the case of commuters who pass by the HOT-lane facility on a regular basis when driving from work to home (not vice versa). In many of these trips, drivers do not have to arrive to their destination at a particular time, and could welcome an occasional faster trip (one that is free or with a lower price than the toll). If such market exists, then the second goal of LBM would be to serve it without degrading the level of service on the HOT lane. And the third goal would be to benefit a potential private operator who, while complying with the targeted level of service, increases revenue (as suggested in Section 4.4.2) by acquiring new customers or increasing the loyalty of existing ones.

An auction-based system may be even more beneficial than LBM. However, during the development of the model in this paper, it became clear that implementing LBM is more challenging than its upgrade to an auction-based system.

Finally, it is worth mentioning two of LBM's properties. First, although new technologies such as geotolling, connected vehicles, and autonomous vehicles would optimize LBM, they are not key for its feasibility. The proposed system relies on the adaptation of technologies used at current HOT facilities and weight stations. Second, LBM does not imply overhauling current HOT facilities. Current HOT users who decide not to use lotteries should not see their current driving experience become affected. Also, the system can be tested at just one entrance and later be scaled up.

This paper is organized as follows. Section 2 presents the literature review. Section 3 provides a self-contained description of an LBM system, as it would be applied to an entrance at the I-394 MnPass Express Lanes in the city of Minneapolis. Section 4 describes the microsimulation model that was used for that entrance, and it tests the LBM system in terms of traffic congestion and revenue changes. These simulation tests always assume that drivers adopt a strategy referred as “safest strategy”. To a great extent, measuring congestion and revenue, under the assumption that the “safest strategy” is implemented, seem to provide enough elements for judging how good the system is. However, Section 4 goes further by also providing information that would allow determining the difference between adopting the safest strategy and what is supposed to be the best strategy. For this reason, the simulation tests also provided the most likely lottery scenarios that drivers would face by answering the following two questions: How many competitors would a driver most likely face when choosing to play the lottery* How many items would most likely be offered in the lottery* Section 5 proposes a game-theoretic model that allows determining what the best strategy is for drivers when facing the dilemma: to pay the toll price, or to participate in the lottery. Because the application of the best strategy presents challenges for its computation, Section 6 looks at how different the best strategy and the safest strategy are in the context of the most likely lottery scenarios obtained in Section 4. Section 7 provides conclusions and recommendations for further research.

2. Previous work

A buyout lottery can be considered as a special case of a buyout auction. In a buyout auction, instead of choosing winners at random, only drivers with the highest bid amounts are chosen. Due to the similarities, previous research on buyout auction theory has contributed to the development of this paper. Buyout auctions exist in websites such as eBay and Yahoo. Most of the research conducted in this area has focused on the sale of one item (Budish and Takeyama, 2001; Caldentey and Vulcano, 2007; Gallien and Gupta, 2007; Grebe et al., 2006; Hidvégi et al., 2006; Mathews, 2004, 2006; Reynolds and Wooders, 2009) but some of it has also focused on simultaneous sales of multiple items (Kirkegaard and Overgaard, 2003, 2008). The latter work assumes that a bidder can obtain more than one item. In the case of a HOT lane, multiple entrance slots are indeed offered simultaneously to participants but only one item can be obtained by each. Another peculiarity of a HOT lane is that paying the toll price guarantees only one item. In a typical auction with a buy price, sometimes choosing the buy price does not guarantee obtaining any item because there may be more participants choosing to buy those items. Another aspect that this paper borrows from auction theory is the concept of “reserve prices” (Krishna, 2009, p. 21).

Part of the research that focuses on single-item auctions (Budish and Takeyama, 2001; Caldentey and Vulcano, 2007; Hidvégi et al., 2006; Mathews, 2004; Reynolds and Wooders, 2009) assumes that bidders are risk averse. This paper follows that assumption by adopting the constant absolute risk averse (CARA) function that Reynolds and Wooders (2009) used. Their function assumes that the utility of obtaining the item is based on the private valuation of the item and the level of risk aversion. Although price is only one reason for why a driver chooses to enter a HOT lane (see for example, Goodall and Smith, 2010, and; Liu et al., 2011), the inclusion of risk aversion and the assumption of the existence of the market described in Section 1 may avoid the need for introducing more factors.

In a recent conference, Olarte and Haghani (2013) presented a generic highway design that allows lottery-based metering. Nonetheless, their design was not tested on a real network and their mathematical model neither allows reserve prices nor allows having more than one entrance slot per lottery.

There is a line a research that has explored auctions on roads. Teodorović et al. (2008) proposed a system in which, for a given urban area, an operator assigns time slots via a combinatorial auction. The time slots could be three to five minutes long within one day or several days. The number of winners that could be assigned to each slot is determined by the parking spaces and the roads in the urban area. Their system does not offer the option of buying a time slot and it cannot be carried out in real time. Thus, drivers are expected to arrive within the time slot that they indicated previously at the auction. Zhou and Saigal (2014) later improved the combinatorial auction by not making winners pay the amount that they bid but less. This system, following the approach of the Vickrey-Clarke-Grove mechanism (Nisan et al., 2007, sec. 9), incentivizes bidders to submit their true valuation. Zhou and Saigal (2014) focused on auctioning road trips and suggested how to apply it to HOT lanes. They proposed real-time communication between vehicles and infrastructure, but they were not specific in the design. Also, their model does not include any buyout option. Collins et al. (2015) looked at the previous work and sought to replace the Vickrey-Clarke-Grove mechanism with a simpler Vickrey auction (Krishna, 2009). Again, they did not focus on the implementation design and they did not include the buyout option in their mathematical model.

3. Lottery-based metering system

This section describes an LBM system that operates on a HOT facility where one of its entrances has the main characteristic of being fed directly by a two-lane arterial. A specific entrance in the city of Minneapolis is used as an example just to give a sense of the possible design values that would characterize the system. The following description is self-contained, although illustrative animations, recently posted by Olarte (2016), could also serve the reader.