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Auction-based highway reservation system an agent-based simulation study ☆

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ABSTRACT

Based on previous studies of a highway reservation system, this paper proposed an auction-based implementation, in which the users can bid for the right to use a route during a certain period of time. This paper models the auction system with MATSim using an agent-based simulation technique. The agents adopt their own bidding logic in the auction, and the price converges after around 130 iterations, when the number of users using the reserved highway and the total collected revenue become stable. When the overall demand changes, the collected revenue ranges from 5 to 11 dollars per user, and from 0.7 to 1.5 dollars per mile. The auction system can transfer more consumer surplus to the toll road operators, since it is a personalized tolling mechanism. The users are using the reservation system as insurance of a guaranteed congestion-free travel. The auction-based highway reservation shows great potential as a new traffic management system.

1. Introduction and background

Adding more capacity by providing additional infrastructure has been one of the most fundamental congestion mitigation solutions in most growing urban regions. However, due to budget constraints and lack of available lands, roadway supply almost always increases at a slower rate than the traffic demand growth. In addition, increasing roadway supply may not be able to alleviate peak-hour congestion since reduction in congestion might induce departure time shifts into peak-hour (Hendrickson and Plank, 1984). As a result, researchers have shifted their focus from the supply side to the demand side, with demand management strategies such as congestion pricing and High-Occupancy-Vehicle/High-Occupancy-Toll lanes (Lou et al., 2011; de Palma and Lindsey, 2011), and parking management (Qian and Rajagopal, 2014). One of the emerging innovative demand management approaches is "highway reservation." The idea behind this is slicing the highway resource into pieces by time and space and allowing users to reserve them in advance so that oversaturation traffic flow does not appear by limiting the total number of reservations. When the highway slots of a certain time interval have been fully reserved, additional users either switch their departure time or use unreserved routes. Different from airline seats, which have clear boundaries, the highway resource does not have a clear edge. Thus, it can be sliced into time intervals and links separated with on- and off-ramps.

A few studies (Wong, 1997; Gerla and Iftode, undated; Iftode et al., undated; Su and Park, 2014) demonstrated the promising performance of the proposed highway reservation system without explicitly considering realistic queuing behaviors and travel times. For example, our previous study (Su and Park, 2014) minimized the total system cost by allocating the

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sliced highway slots to the users. In the two case studies, the optimized system costs were at least 20% lower than corresponding user equilibrium conditions. An important finding is that in the optimized trip schedule, all the link flows are under capacity, even though the model did not have a capacity constraint. This finding justifies bringing a capacity constraint through a reservation system. An optimized trip schedule is a centralized way of allocating the highway resource to users, based on assumptions of homogeneous users and 100% compliance rate. However, this is not the case in real life. That's why we propose a multi-agent-based model to simulate users' heterogeneous behaviors in an auction system.

Here is how it works: A reservation center operates the highway in a metropolitan area. The travellers notify the reservation center their desired route and on-ramp entrance time interval, and put in a bid for it. The reservations are handled in a sequence of the bids from high to low. When a link in the requested route has been fully reserved, that request is rejected, and the user either submits a new request with a higher bid or a different time interval the next day. If all of the links of the requested route are available, the request is accepted and the user is charged the amount of the bid.

In this paper, an auction system is proposed over a First-Come-First-Serve (FCFS) rule in the reservations. FCFS policy works in many reservation-based-scheduling services like doctors' offices and vehicle maintenance, in which users with strong preferences for certain times will typically be the "first-comers" to reserve that time. However, when traffic congestion becomes such a big problem and everyone wants to be "first-comers", the FCFS rule will not work. For example, all users want to reserve a 7:30 am time, and they all submit the reservation request right after the system opens. If the system is web-based, that probably means the sequence of receiving these requests are based on milliseconds difference, making FCFS an infeasible solution.

What's the advantage of a reservation system over a time-varying toll? The toll on a High-Occupancy-Toll (HOT) system can change by the travel distance and by the overall demand level, but not by users or vehicles. The beauty of an auction system is that price is directly determined by the users through competition, or market. So an advantage of a reservation system is varying the toll by users. A major problem with HOT systems is that users sometimes are not quite sensitive to the price, and increasing the toll may not avoid a break down in a HOT lane. This problem is solved in the reservation system by the imposing a capacity constraint.

The contribution of this paper is to explore the feasibility of implementing a highway reservation system using an auction-based approach. Auction theory focuses on single commodity auctions, while the highway slots are in thousands, and they are not independent. For example, if the freeway link between ramp 2 and 3 at 8:30 am are fully reserved, all the other routes that need this link at 8:30 am, including from ramp 1 to 3 or from ramp 2 to 4 become unavailable. An agent-based simulation technique is adopted to study such a complicated auction structure. The remainder of the paper is organized as follows: Section 2 briefly discusses previous studies and highway reservation concepts and other auction-based traffic management, followed a description of the auction-based reservation architecture. Section 4 describes the traffic network structure of a case study and its travel demand using an OD matrix. The "Results" section describes the simulation outputs and findings. Section 9 presents the issues that need to be considered but not modelled in this paper. Finally, Section 10 highlights the findings from the simulation, and future research ideas.

2. Literature review

The concept of road reservation or trip-booking is mentioned in the literature as early as the 1990s (Wong, 1997; Gerla and Iftode, undated; Iftode et al., undated). Wong (1997), Gerla and Iftode (undated), and Iftode et al. (undated) discussed basic functions, advantages and difficulties of a highway booking system. Extensive modelling efforts were not done until the past 5 years. McGinley et al. (2010) showed that a reservation system is necessary to avoid waiting when the mean waiting time is large at the optimal point of operation. Studying the reservation system on a single bottleneck with heterogeneous users, Koolstra (2000) found all queuing costs can be eliminated without increasing the mean rescheduling costs. Another finding is that a freeway reservation might be more effective in practice than road pricing. de Feijter et al. (2004) showed that trip booking can improve reliability and predictability of travel times. Since travel time uncertainty can account for a large proportion of the morning commute cost (Robert and Small, 1995), the improvement of travel time reliability could be a huge benefit of the reservation system. Edara and Teodorovic (2008) conducted extensive modelling work of reservation systems, proposing a Highway Allocation System (HAS) and a Highway Reservation System (HRS). The goal of HAS is maximizing the total Passenger-Miles-Travelled over a period by selecting trips from received booking requests. HRS assumes an incoming booking request flow and makes an on-line decision to accept or reject a request. A potential limitation with HAS is using Passenger-Miles-Travelled as objective, as it is biased toward longer distance trips. HAS did not consider explicitly the departure time adjustment, which is the core role of reservation systems.

Due to the fact that highway does not have separable seats like airplanes, researchers have proposed different methods to discretize the highway resource. The most common one is slicing highway capacity by links and time intervals (Wong, 1997; Gerla and Iftode, undated; Iftode et al., undated; Ravi et al., undated). Liu et al. (2013) used a different approach: a token-based reservation idea from computer science domain. Each road segment has a set of tokens. A vehicle has to be affiliated with a token to travel on that segment. When it arrives at the next road segment, there should be a token on that segment available for this car. Tokens can be reused by multiple vehicles as long as the requested time slots on the token do not overlap. The total number of tokens is the product of the segment length and optimal traffic density, which is determined by Greenshield's model. Thus, the optimal density is a half of jam density, and optimal speed is a half of free flow speed. A critical challenge with this approach is that the amount of time a car occupies a token is hard to determine, since the travel time depends