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A scalable non-myopic dynamic dial-a-ride and pricing problem for competitive on-demand mobility systems

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ABSTRACT

We propose a competitive on-demand mobility model using a multi-server queue system under infinite-horizon look-ahead. The proposed approach includes a novel dynamic optimization algorithm which employs a Markov decision process (MDP) and provides opportunities to revolutionize conventional transit services that are plagued by high cost, low ridership, and general inefficiency, particularly in disadvantaged communities and low-income areas. We use this model to study the implications it has for such services and investigate whether it has a distinct cost advantage and operational improvement. We develop a dynamic pricing scheme that utilizes a balking rule that incorporates socially efficient level and the revenue-maximizing price, and an equilibrium-joining threshold obtained by imposing a toll on the customers who join the system. Results of numerical simulations based on actual New York City taxicab data indicate that a competitive on-demand mobility system supported by the proposed model increases the social welfare by up to 37% on average compared to the single-server queuing system. The study offers a novel design scheme and supporting tools for more effective budget/resource allocation, planning, and operation management of flexible transit systems.

1. Introduction

The sharing economy provides opportunities for individuals in both the buying and sharing of products or services. Sharing-economy platforms allow people to find temporary employment, generate extra income, increase reciprocity, enhance social interaction, and access resources that are otherwise unattainable. Uber and Airbnb are among the world's leading businesses in transportation and hospitality, respectively. While many municipalities and regions have blocked these new forms of commerce, others have accepted change as inevitable and have been eager to provide new efficiencies for consumers. For example, Hall and Krueger (2016) argue that the availability of modern technology such as the Uber app provides numerous advantages, including lower consumer fares and potentially higher earnings for drivers, over the traditional taxicab dispatch system. Although the sharing economy is profitable, little is known about its use among unemployed and low-income individuals and families. Some reports suggest that this new platform of economic activity is highly insecure and that contingent employment leads to the exploitation of workers (Summers and Balls, 2015). Bernhardt (2014) signals a cautionary note about any claims of radical recent change being wrought across the U.S. economy and identifies data gaps that need to be closed and research questions that need to be answered in order to improve workplace and labor standards. For example, why is the traditional taxicab dispatch system unable to compete with or rival the new forms of commerce, and does the sharing economy really provide benefits? One key aspect of our smart on-demand transit approach is social efficiency, in terms of both the level of service and the computational effort needed to operate it.

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For a traditional taxicab dispatch system, the first–last mile problem is challenging because it calls for high flexibility under relatively low-density usage, which implies a high cost to implement. As an example, taxicab drivers in New York City (NYC) spent 39% of their total mileage cruising for passengers in 2005 (see Schaller Consulting, 2006). Such a system is often inefficient, because of the use of expensive vehicles, high fuel costs, heavily congested traffic, and a low ratio of busy to idle vehicles (see Powell et al., 2011). In addition to the costs, this is a major environmental concern, since the burning of fossil fuels in vehicles is a major contributor to global warming. If ridesharing systems and other forms of public transit increase in efficiency, fewer people will rely on personal vehicles to meet their transport needs. Thus a smart on-demand system could be a significant step in reducing costs and carbon emissions worldwide.

The state of a transit system can change rapidly, and static models lack the flexibility to adapt to changes in a timely manner. Because they ignore the elasticity of demand and price, such models can result in inefficiencies that stem from overestimation of improvements in the level of service—a limitation that could be reduced or eliminated if non-myopic considerations were taken into account. Thus what is needed is a smarter system that anticipates stochastic elements and dynamically adapts to them. Among other things, such a system should be able to incorporate high-speed-communication technologies in order to calculate opportunity costs, so that social benefits can be divided between customers and providers—a prospect which has been ignored in traditional transit systems.

Real-time information problems introduce a new dimension to decision-making in dynamic models. These models involve an iterative process: making decisions, then accessing information, then making more decisions and accessing more information, and so on. A Markov decision process (MDP) with discrete time intervals can be modeled using a Bellman equation (Powell, 2011), as follows:

$$\mathrm{V_t(S_t)} = \min_{\mathrm{x_t}}(\mathrm{C_t(S_t,x_t)} + \gamma \mathrm{E[V_{t+1}(S_{t+1})|(S_t,x_t)]}), \tag{1}$$

where $\mathrm{V_t}$ is the value of the optimal dynamic policy, $\mathrm{C_t}$ is the immediate payoff of the decision x_t under state S_t (which is also typically driven by information on exogenous stochastic variables, and varies in size based on the underlying distribution of the variable(s)), and γ is a discount factor. The conditional expectation term depends on the future state while it depends on the state S_t which defines as location of vehicles and may also depend on x_t. It can cost time and money to visit a state, so we have to consider the future value of an action in terms of its effect on improving future decisions. As a result, we need to estimate the value function at a given state, which necessitates a tradeoff between visiting that state because we think it represents the best decision ("exploration") and estimation of downstream values to make what we think is the best possible decision ("exploitation"). As a result, the Bellman equation becomes one that depends on both past (through network effects) and future (through the expected value function). Sayarshad and Chow (2015) proposed an approximation method in which the network effects and the timing effects as illustrated with an intermediate value function (based on Chow and Regan, 2011; Chow and Sayarshad, 2015) from Eq. (1) are lumped together into one effect:

$$V_{t,i}(S_t) = \min_{\mathrm{x_{t,i}}}(C_t(S_t,x_{t,i}) + \Omega(V_{t,1},...,V_{t,i-1},V_{t,i+1},...,V_{t,K},E[V_{t+1}|S_t])), \tag{2}$$

where K is the number of link components for which decisions must be made, Ω is approximated by an expression derived from an M/M/s queue, and the whole expression is split into user costs and system costs. The state of all vehicles constitutes the state of the system at time t, denoted as S_t. The approach we propose in this study is not limited to only a single time-step look-ahead and instead exploits our estimates of the value function under an infinite-horizon look-ahead.

Autonomous vehicles (AVs) are potentially disruptive, both technologically and socially, with claimed benefits comprising increased safety, road utilization, energy savings, and driver productivity (Zhang and Pavone, 2016, Ma et al., 2017a). For example, it has been asserted that if five percent of new vehicles sold in 2030 (about 800,000 vehicles) were shifted to autonomous taxis, it would save about 7 million barrels of oil per year and reduce annual greenhouse gas emissions by 2.1–2.4 million metric tons of CO_2 per year, which is equal to the emissions savings from more than a thousand 2-megawatt wind turbines (Greenblatt and Saxena, 2015; Greenblatt and Shaheen, 2015). The technology which is needed to enable automation, particularly at levels 3–5 (based on the levels of AVs which have been defined by The National Highway Transportation Safety Administration), is extremely sophisticated and would have to make use of high-performance computational hardware, state-of-the-art online models, decision-making algorithms, and real-time information. Our proposed methodology could possibly be applied as a decision support tool for future urban mobility systems such as smart taxis and autonomous vehicle fleets. The smart system could also offer numerous transportation, infrastructure, land use, and environmental benefits (increased overall public transit and non-motorized modal use, including rail, walking, bicycling, and carpooling), as well as social benefits (access by college students; availability in rural, suburban, and disadvantaged communities; reduced stress on commuters; and often preferential parking and other incentives). As a result, the potential energy savings expected from AVs are much larger than the estimated worst-case growth in energy use and other factors (see Greenblatt and Shaheen, 2015). Smart on-demand mobility systems would therefore be a valuable alternative to personal vehicles; they would also be a help to communities with poor or nonexistent public transit, such as low-income communities, rural areas, and large suburbs.

The framework for our proposed system, where dynamic operations are driven by real-time information, is shown in Fig. 1, which lists the various technologies and data sources needed to ensure a viable "smart" transit system. For example, communications equipment is needed so that customers can send travel requests to the dispatch center. Intelligent vehicle-highways systems (IVHS) is an application of information and communications technologies (ICT) that could bring about better control of the flow of vehicles. Electronic data interchange (EDI) consisting of the electronic transfer from computer to computer could increase the speed of