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Stochastic dynamic switching in fixed and flexible transit services as market entry-exit real options

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ABSTRACT

The first analytical stochastic and dynamic model for optimizing transit service switching is proposed for "smart transit" applications and for operating shared autonomous transit fleets. The model assumes a region that requires many-to-one last mile transit service either with fixed-route buses or flexible-route, on-demand buses. The demand density evolves continuously over time as an Ornstein-Uhlenbeck process. The optimal policy is determined by solving the switching problem as a market entry and exit real options model. Analysis using the model on a benchmark computational example illustrates the presence of a hysteresis effect, an indifference band that is sensitive to transportation system state and demand parameters, as well as the presence of switching thresholds that exhibit asymmetric sensitivities to transportation system conditions. The proposed policy is computationally compared in a 24-hour simulation to a "perfect information" set of decisions and a myopic policy that has been dominant in the flexible transit literature, with results that suggest the proposed policy can reduce by up to 72% of the excess cost in the myopic policy. Computational experiments of the "modular vehicle" policy demonstrate the existence of an option premium for having flexibility to switch between two vehicle sizes.

1. Introduction

The potential of optimal timing and control of transit systems under uncertainty continues to grow in today's data-driven environment. There are countless examples of such applications, including: determining when to allow fixed-route services to deviate; optimal holding strategies for buses; adjusting size of vehicle groups (e.g. trains) that are dispatched; positioning idle on-demand vehicles; and determining "price surges". However, there are very few fundamentally general analytical methods available to time decisions under dynamic uncertainty in this domain. In this study, we explore one such timing method based on real options theory, and evaluate its effectiveness in well-studied problems of time-dependent changes between two different transit fleet operating modes.

It has long been known that different demand density levels warrant transit services with different operating policies and degrees of flexibility (Saltzman, 1973; Jacobson, 1980; Adebisi and Hurdle, 1982). Some studies sought to determine thresholds based on demand densities between different transit services, including fixed-route and flexible-route systems

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(Daganzo, 1984b; Chang and Schonfeld, 1991a; Quadrifoglio and Li, 2009; Qiu et al., 2015). Several studies have examined the problem of integrating fixed-route and flexible-route transit, primarily under the many-to-one service setting which applies either to last mile service design or to monocentric city structures (Chang and Schonfeld, 1991b; Kim and Schonfeld, 2013, 2014; Sun et al., 2017). These include joint design of fixed transit lines and feeder services (e.g. Kim and Schonfeld, 2014). With advances in artificial intelligence and autonomous vehicle technologies, as illustrated in Fig. 1, and with planned deployments in Dubai (Spera, 2016) and Singapore (Ackerman, 2016), algorithms for optimal control of fleet systems over time are more urgent than ever. For example, autonomous vehicle fleets may be dynamically switched between fixed-route and on-demand operations.

The literature includes several studies for optimizing the assignment of transit vehicles to fixed or flexible services. Kim and Schonfeld (2012) proposed an analytical model framework for comparing operations among fixed-route only, flexible-route only, and an integrated service that temporally switches between the two during peak and off-peak periods. Quadrifoglio and Li (2009) and Qiu et al. (2015) examined analytical models of transit services that deviate from fixed routes to provide flexible drop-offs, and where to deterministically switch between them (Li and Quadrifoglio, 2010). Kim and Schonfeld (2013, 2014) proposed an integrated service model that can alternate service types over both time and multiple sub-regions. Some studies have also explored with optimization models how mixed fleets consisting of multiple vehicle types or sizes should be allocated among various transit services (Lee et al., 1995; Fu and Ishkhanov, 2004), and how such mixed fleets should be switched between different transportation services at different times (Kim and Schonfeld, 2013). There are multiple forms of transportation services considered as flexible transit services, such as dial-a-ride (Marković et al., 2015) and share-a-ride (Li et al., 2016). Errico et al. (2013) present a systematic survey of flexible transit services from a planning perspective and Frei et al. (2017) assess the demand for such flexible transit using a stated preference approach.

All these integrated service options are static policies since they are not designed to adapt to new information, and thus fail to exploit advances in increasingly pervasive information and communications technologies (ICTs). Dynamic flexible transit services (Djavadian and Chow, 2017) have become such a viable alternative for serving passengers that many new service providers have cropped up in the private sector alone: e.g. Uber, Lyft, Via, RideCo, and Bridj. In this context, there have been studies optimizing the dynamic routing (see Psaraftis et al., 2016), dynamic pricing (Sayarshad and Chow, 2015), dynamic vehicle waiting strategies (Thomas, 2007), and dynamic relocation of idle taxis (e.g. Yuan et al., 2011). Studies have not looked at the problem of dynamically allocating or switching vehicles between fixed and flexible routes under time-variant uncertainty.

We propose to modify the static fixed/flexible service policy in the literature into a stochastic, dynamic policy in a many-to-one (M-to-1) system. This very adaptable M-to-1 structure, shown in Fig. 2, supports many applications: monocentric city designs, last mile problem, planned event logistics, and multimodal infrastructure planning, to name a few. As noted in Chang and Schonfeld (1991a), multiple such structures that are connected at a central terminal can serve many-to-many (M-to-M) demand patterns, thus connecting all possible origin destination pairs in an urban region with at most one transfer. However, this study focuses on the M-to-1 system. For example, this setting includes having a fixed-route trunk transit

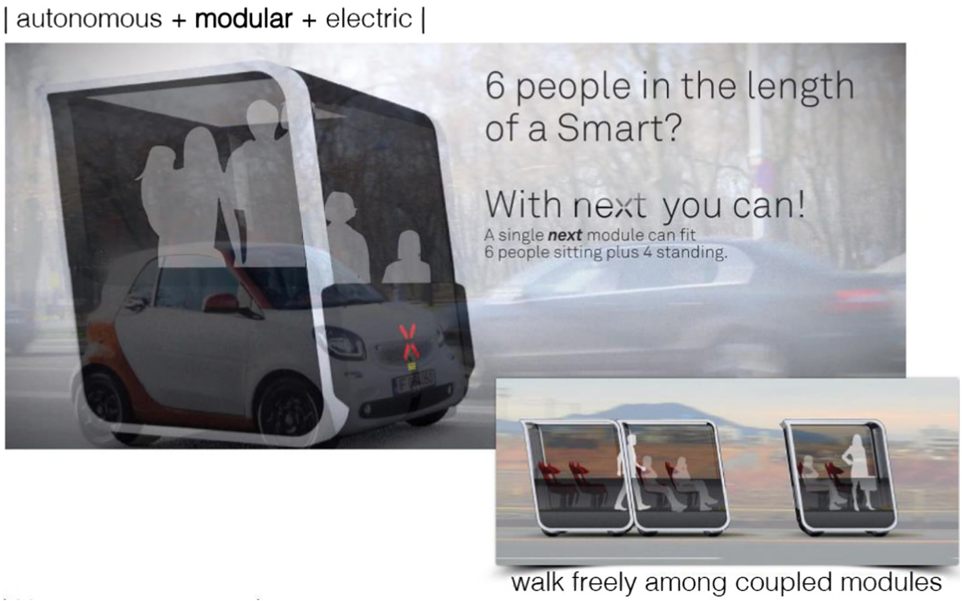

Fig. 1. Illustration of shared autonomous fleets with modular vehicle size. *Source:* www.next-future-mobility.com.

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