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First-Best Dynamic Assignment of Commuters with Endogenous Heterogeneities in a Corridor Network

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Abstract

We study a parsimonious theory that synthesizes short-term traffic demand management (TDM) policies with long-term endogenous heterogeneities of demand. In a corridor network with multiple discrete bottlenecks, we study a model of system optimal assignment that integrates the short-term problem (departure time choice with tolling) and the long-term problem (job and residential location choice). For the short-term departure-time-choice equilibrium, under mild assumptions on schedule delay function, we derive analytical solutions under a first-best TDM scheme. Investigating properties of long-term equilibria, we found that the overall equilibrium pattern exhibits remarkable spatio-temporal sorting properties. It is further shown that a lack of integration of the short- and the long-term policy results in excessive investments for long-term road construction.

Keywords: departure time choice, job-location choice, corridor problem, user heterogeneity, dynamic system optimal assignment

1. Introduction

1.1. Background and purpose

Alleviating traffic congestion in the morning peak hours is one of the most significant challenges in transportation science. Parsimonious and rich in insights, the standard departure-time choice equilibrium model with a single bottleneck (Vickrey, 1969; Hendrickson and Kocur, 1981; Arnott et al., 1990) and its extensions have long been the workhorse for tackling the problem, yielding a large body of theoretical studies (e.g. Smith, 1984; Daganzo, 1985; Newell, 1987; Lindsey, 2004; van den Berg and Verhoef, 2011; Liu and Nie, 2011). Even though researches have successfully provided deep implications for the short-term TDM policies, when it comes to the long term, there is room for further investigation. In the long term, what is given in the short term is endogenous. Origin–destination demand patterns might vary over time because of residential location choice of commuters; commuters can also switch their jobs, thereby affecting value-of-time (VOT) distribution over commuters. Such long-term endogenous variations in

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demand inevitably affect long-term effectiveness of short-term TDM policies. Extending the short-term framework to incorporate long-term demand dynamics thus seems to be a valuable direction of study.

The purpose of the present paper is to introduce a parsimonious theory that synthesizes long-term endogenous heterogeneities of traffic demands with the short-term TDM policy. To this end, keeping the model as compact as possible, we extend the standard bottleneck model to allow each commuter to choose his/her own residential location and job in the long-run, so that *endogenous commuter heterogeneities* emerge. Also, our analysis is conducted in a corridor network with *multiple bottlenecks* à la Akamatsu et al. (2015) to allow rich spatial and temporal dynamics.

We first prove that, under the short-term first-best policy, any integrated equilibrium for the whole problem is Pareto-efficient. We also show that there is an equivalent optimization formulation that is a highly structured linear programming problem, whose structure yields a natural decomposition into the two components of the short- and the long-term. We further show that the short-term component (departure time choice equilibrium) is *analytically solvable* under mild assumptions on the schedule delay function.[1]

Interestingly, equilibrium job–location–departure-time choice patterns are shown to exhibit striking *sorting regularities* in both the short- and the long-term. In the short-term equilibrium traffic flow, we observe a job- and location-based *temporal sorting*. Specifically, (i) commuters who work for jobs with higher VOT arrive at the CBD at times closer to their desired arrival time, and (ii) commuters who reside at distant locations have strictly longer arrival time window. In the long-term equilibrium patterns, we observe a job-based *spatial sorting*, where commuters who work for jobs with higher VOT choose to live closer to the CBD.

As a major policy implication, we show that, without integration of the short- and the long-term TDM policy, the total investment for bottleneck capacity is overestimated; without consideration of the long-term decision of commuters, the road manager results in excessive extension of road capacity.

1.2. Related literature

To date, only Arnott (1998), Gubins and Verhoef (2014), and Takayama and Kuwahara (2016) have developed dynamic bottleneck models that include location choice of commuters. Our study extends the scopes of these studies in two ways. First, without sacrificing tractability, we generalize the single bottleneck setup to a corridor with multiple bottlenecks. The setting allows us to examine richer spatial dynamics in both the short and the long term. Second, we allow endogenous job choices that determine commuter heterogeneities (regarding their VOT), which is novel.

For the short-term component, our study formulates a dynamic system optimal (DSO) assignment which is achieved as the *equilibrium* under a short-term TDM scheme that eliminates the bottleneck queues. A DSO assignment problem with similar network setting (a freeway corridor with multiple discrete on- and off-ramps) is studied by Shen and Zhang (2009). Tian et al. (2012) is also in related direction, albeit the model is formulated via a continuum approximation à la Arnott and de Palma (2011). The prevalent problem is that analytical solutions are hard to obtain even when one assume piecewise linear schedule delay and homogeneous commuters. We contribute to this literature by providing analytical solutions (i.e., equilibrium traffic flow, equilibrium commuting cost) under mild assumptions on the schedule delay function, as well as allowing commuter heterogeneity.

2. Model

Consider a freeway corridor that connects I residential locations to a central business district (CBD), as illustrated by Fig.1. The residential locations are indexed sequentially from the CBD. We denote the set of locations by $\mathcal{I} \equiv \{1, 2, \ldots, I\}$. There is a single bottleneck with capacity μ_i just downstream of the on-ramp from the location $i \in \mathcal{I}$, which we call the "bottleneck i". Dynamic queueing at the bottlenecks are modeled by the standard point queue model along with first-in-first-out; at each bottleneck, a queue is formed vertically when the inflow exceeds the capacity. Each residential location $i \in \mathcal{I}$ is endowed with A_i unit of land. At the CBD, there are J job opportunities. The labor demand and the VOT for each job $j \in \mathcal{J} \equiv \{1, 2, \ldots, J\}$ are given by L_j and α_j, respectively.

[1] The result contrasts to previous studies which usually assume piecewise-linear schedule delay. This generalization becomes possible partly because we consider dynamic system optimal assignment. Nonetheless, it is noted that the basic strategy presented in this paper is effective and can be used to tackle dynamic user equilibrium assignment in a corridor network (Fu et al., 2016).