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Activity-based market equilibrium for capacitated multimodal transport systems

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ABSTRACT

Empirical studies have shown that demand for multimodal transport systems is highly correlated with activity schedules of individuals. Nonetheless, existing analytical equilibrium models of multimodal systems have only considered trip-based demand. We propose a new market equilibrium model that is sensitive to traveler activity schedules and system capacities. The model is based on a constrained mixed logit model of activity schedule choice, where each schedule in the choice set is generated with a multimodal extension of the household activity pattern problem. The extension explicitly accounts for both passenger choices of activity participation and multimodal choices like public transit, walking, and vehicle parking. The market equilibrium is achieved with Lagrangian relaxation to determine the optimal dual price of the capacity constraint, and a method of successive averages with column generation finds an efficient choice set of activity schedules to assign flows over the dynamic network load capacities. An example illustrates the model and algorithm, effects similar to Vickrey's morning commute model can be observed as a special case. A case study of the Oakville Go Transit station access "last mile" problem in the Greater Toronto Area is conducted with 166 survey samples reflecting 3680 individuals. Results suggest that a $10 fixed parking fee at Oakville station would lead to a reduction of access auto share from 54.8% to 49.5%, an increase in access transit share from 20.7% to 25.9%, and a disutility increase of 11% for the of single-activity residents of Oakville.

1. Introduction

With increasing urbanization and ubiquity of information communications technologies (ICTs), the need and opportunity for urban agencies to consider new ICT-driven mobility systems and transportation business models have never been greater. This is evident in the quickly changing landscape of multimodal transport services from the private sector: companies that offer car sharing, advanced parking management systems, demand responsive shuttle or taxi services, among others. Despite such interest, the public sector has largely not been able to reap the benefits of these alternative operating designs. Unlike private firms, urban agencies need to consider the effect of a system design on the public welfare and measure its supply–demand equilibrium, as with any transportation system (Manheim, 1976; Florian and Gaudry, 1980). Even in settings where multimodal systems may be well-suited, such as last-mile operations to connect users from transport hubs to their final origins/destinations, many agencies find themselves lacking decision support tools to do so.

The underlying problem is that multimodal systems, more so than traffic systems, need to explicitly consider the users' daily schedule constraints as well as the systems' schedules. Travelers participate in a number of activities in which they

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have desired arrival times (Small, 1982; Chow and Recker, 2012), from which they may schedule transport services. Choices in travel mode and activity agenda are highly inter-related. For example, leaving a car at home to take transit will not only impact an individual's morning commute, but will also affect subsequent trip choices and schedule throughout the day. As argued by Kang et al. (2013), these schedule effects can be much more dominant in the user behavior for multimodal systems than in traffic networks. In essence, an equilibrium model of multimodal systems needs to account for both the scheduling behavior of users and the capacity effects of the system.

Much of the literature on equilibrium models of multimodal systems, however, relies on either (1) traffic equilibrium extensions that base the mode choice decision purely on congestion effects during a peak period (e.g. Abdulaal and LeBlanc, 1979; Dafermos, 1982; Wu et al., 1994; Cantarella, 1997; Lam et al., 1999; Kurauchi et al., 2003; Lo et al., 2004; de Cea et al., 2005; Li et al., 2007), on (2) Vickrey's (1969) morning commute variations (e.g. Arnott et al., 1991; Tian et al., 2007; Qian and Zhang, 2011; Gonzales and Daganzo, 2012), or on (3) agent-based simulations (e.g. MATSim – Rieser, 2010; MILATRAS – Wahba and Shalaby, 2014). While traffic equilibrium extensions capture congestion effects in peak period travel choices, they ignore trip chains and user scheduling behavior throughout the day. Bottleneck models offer a high level view of time-dependent choices for policy analysis, but do not capture the trip chaining behavior for a full activity agenda. None of these offer an analytical equilibrium model that considers both system capacities and activity scheduling behavior of users.

A few studies have analytically "assigned" users to activity-based schedules. Li et al. (2010) proposed an activity assignment equilibrium model that considers fixed route transit services, but individual spatial–temporal constraints inherent in individual scheduling behavior are not modeled. Liao et al. (2013) considered multimodal options using supernetworks of access states. Recker (1995) proposed a model that assigns individuals to daily activity schedules in a mathematical programming structure that is conducive to duality analysis, and can be calibrated to observations from household travel diaries (Chow and Recker, 2012). However, it does not model multimodal options, and neither it nor Liao et al.'s (2013) model consider equilibrium between individuals in a congested or capacitated system.

We propose a market equilibrium model for multimodal transport systems that captures both the capacity effects of a transport system and the traveler activity scheduling behavior. The model is based on an extension of Recker's (1995) Household Activity Pattern Problem (HAPP) to (1) accommodate multimodal travel choices, and (2) to aggregate the choices of a sample of users to the population while constraining them within the load capacity. Neither of these contributions is trivial, as they require significant modifications to the graph structure and use of Method of Successive Averages (MSA) and column generation algorithm (by exploiting the duality property of the model) to construct the choice set of a spatial–temporally constrained mixed logit model under dynamic network capacities. Unlike other multimodal equilibrium models, this is the first *disaggregate activity scheduling assignment* via sampled vehicle routing problems (HAPP models) and aggregated in a manner that is consistent with a spatial–temporal constrained mixed logit model of traveler activity schedule choice.

The paper is organized as follows. Section 2 provides a review of the need for activity scheduling in transit design, and how the HAPP model handles the former but not the latter. Section 3 presents the proposed multimodal extension to the HAPP model and a mixed logit based MSA and column generation solution method that accounts for dynamic network load capacity. Section 4 provides a replicable example that illustrates the model and solution method, and Section 5 presents a case study of the model used to analyze a park-and-ride facility in the Oakville Go Transit hub in the Greater Toronto Area using the 2011 Transportation Tomorrow Survey (TTS) data obtained from the Data Management Group (DMG, 2014).

2. Literature review

2.1. Activity scheduling

A number of studies give empirical evidence that mode choice behavior is highly dependent on factors outside of a single trip (Miller et al., 2005), such as activity agendas participated by the individual throughout the day (Bhat, 1997; Jonnalagadda et al., 2001). These studies suggest that activity-based scheduling choices of travelers are needed to appropriately model the demand equilibrium for multimodal transport systems. The roots of activity scheduling (or activity routing) began from the efforts of social scientists and economists to try to understand why and how people travel (time geography: Hägerstrand, 1970) and how they make use of their time (time allocation: Becker, 1965). In recent years, three general classes of activity routing models have been proposed: a network equilibrium approach that focuses on congestion effects on activity networks; a multimodal supernetwork approach that captures transitions between different modes in space and time as states; and deterministic utility maximization under space–time constraints as a series of integer programming problems per household.

Lam and Yin (2001) first introduced an activity-based equilibrium model, which looks at activity patterns from an aggregate perspective. As such, congestion effects can be captured with a discrete time-expanded network and the assumption that choices made earlier in the day are independent of choices later in the day. The model has been extended to include parking (Huang et al., 2005), multimodal systems (Li et al., 2010) stochastic utilities (Fu and Lam, 2014), weather effects (Fu et al., 2014), dynamic traffic assignment consideration (Ma and Lebacque, 2013), and energy use (Nourinejad et al., 2015). The model has been shown to be a more generalized form of the Vickrey bottleneck model (Li et al., 2014).