Transportation Research Part B 68 (2014) 262–287

Contents lists available at ScienceDirect

Transportation Research Part B

journal homepage: www.elsevier.com/locate/trb

Bottleneck model revisited: An activity-based perspective

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ARTICLE INFO

Article history:
Received 25 October 2013
Received in revised form 19 June 2014
Accepted 19 June 2014

Keywords:
Bottleneck model
Tour
Trip-based approach
Activity-based approach
Marginal-activity utility function
Flexible work-hour scheme

ABSTRACT

The timing of commuting trips made during morning and evening peaks has typically been investigated using Vickrey's bottleneck model. However, in the conventional trip-based approach, the decisions that commuters make during the day about their activity schedules and time use are not explicitly considered. This study extends the bottleneck model to address the scheduling problem of commuters' morning home-to-work and evening work-to-home journeys by using an activity-based approach. A day-long activity-travel scheduling model is proposed for the simultaneous determination of departure times for morning and evening commutes, together with allocations of time during the day among travel and activities undertaken at home or at the workplace. The proposed model maximizes the total net utility of the home-based tour, which is the difference between the benefits derived from participating in activities and the disutility incurred by travel between activity locations. The properties of the model solution are analytically explored and compared with the conventional bottleneck model for a special case with constant marginal-activity utility. For the case with linear marginal-activity utility, we develop a heuristic procedure to seek the equilibrium scheduling solution. We also explore the effects of marginal-work utility (or the employees' average wage level) and of flexible work-hour schemes on the scheduling problem in relation to the morning and evening commuting tours.

1. Introduction

The bottleneck model introduced by Vickrey (1969) has been recognized as a benchmark representation of the dynamics of peak-hour traffic congestion due to its ability to capture the essence of congestion dynamics in a simple and tractable way. The standard bottleneck model has been extended in numerous ways, such as by considering heterogeneous travelers (Arnott et al., 1988, 1992; Lindsey, 2004; Qian and Zhang, 2013; van den Berg, 2014), bottleneck congestion pricing (van den Berg and Verhoef, 2011, 2014; Xiao et al., 2011, 2012; Lindsey et al., 2012), bottleneck capacity expansion (Arnott et al., 1990; Arnott and Kraus, 1995), interaction between parallel or serial bottlenecks (Huang and Yang, 1996), mode substitution (Tabuchi, 1993; Huang, 2002; Huang et al., 2007; Gonzales and Daganzo, 2013), and recently, designing tradable credit schemes (Nie and Yin, 2013; Xiao et al., 2013) and considering stochastic bottleneck (Fosgerau and Lindsey, 2013;

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http://dx.doi.org/10.1016/j.trb.2014.06.013
0191-2615/

Siu and Lo, 2013; Xiao et al., 2014). Arnott et al. (1993) provided a structural definition of the bottleneck model and illustrated its application in the assessment of various congestion toll-pricing schemes. For a comprehensive review, readers can refer to Arnott et al. (1998) and Lindsey and Verhoef (2001).

Vickrey's bottleneck model and its variations usually treat a single-trip scheduling problem by modeling the trade-off between bottleneck congestion and schedule delay, and thus falls into the trip-based modeling framework. Trip-based models do not explicitly recognize the motivations or reasons for trips, and simply use discrete trips as the standard travel unit. Thus, they cannot reflect the links among trips, the links between trips and activities, and the temporal constraints and dependencies of participation in the activities concerned (Kitamura, 1988; Lam and Yin, 2001; Lam and Huang, 2002; Fu and Lam, 2014). As a result, the trip-based approach cannot properly capture the activity and travel-choice behavior of individuals or their allocations of time during a day among activities and travel, which may lead to biased or distorted evaluations of transport policy influence on individuals' activity-travel scheduling (Li et al., 2010).

In reality, the departure-time choices of commuters leaving home in the morning and their workplaces in the evening are usually related to the utilities of home and work activities in addition to the factors of bottleneck congestion and schedule delay (Zhang et al., 2005; Ettema et al., 2007; Jenelius et al., 2011; Jenelius, 2012). For example, when the home activity in the morning (e.g., preparing breakfast for the children) has a higher marginal utility than the work activity, the commuter may leave home late to achieve a high level of utility from participating in the home activity. Conversely, when the marginal utility of the work activity is higher than that of a home activity (e.g., a high overtime payment), the commuter may stay in the office for a longer time. In addition, when the home activity in the evening (e.g., family dinner, watching television or sleeping) has a higher marginal utility than the work activity, the commuter may leave the office early to perform more home activities in the evening. Hence, it is of great importance that the activity-scheduling behavior of the commuters is incorporated into the traditional bottleneck model, such that the effects of activity utility on the commuters' departure-time choices and time-use decisions can be revealed.

It has been widely recognized that the activity-based approach can serve as a powerful tool for understanding activity-travel scheduling behavior (Kitamura, 1988). Activity-based models consider travel as demand derived from the need to participate in activities at different points in space and time, and individuals' activity-travel patterns as the results of time-use decisions within a continuous time domain (e.g., a day). In activity-based models, travel patterns are organized as sets of related trips known as "tours." These tours are chains of multiple trips that begin and end at the same point, such as the commuter's home. Activity-based models can address the interdependencies of trips and activities in time and space and the time-use decisions that individuals make during the day. For more details on the activity-based approach, readers can refer to Jones et al. (1990), Ettema and Timmermans (1997), and Timmermans (2005). In this paper, we propose an activity-based bottleneck model to address the interactions between commuters' time allocations among their activities and travel and the dynamics of bottleneck congestion.

The standard bottleneck model also focuses mainly on morning commuting trips in which commuters are assumed to care about when they depart from their homes. Little attention has been paid to evening or day-long commuting problems. This may have arisen because the evening commuting trip is usually considered to be a symmetric reverse process of the morning trip. Some previous studies, such as those by Vickrey (1973), Hurdle (1981), Fargier (1983), de Palma and Lindsey (2002a) have investigated morning and evening departure patterns in isolation and shown that the morning and evening departure patterns of specific individuals were symmetric (i.e., the departure pattern of the morning commute was a mirror image of that for the evening commute). However, this symmetry tends to break down with increased heterogeneity among commuters in terms of their preferred work start/end times, the value of their time and the costs of schedule delays. De Palma and Lindsey (2002b) illustrated this lack of symmetry in the presence of congestion toll pricing.

Although investigating the morning and evening commuting problems in isolation provides some important insights, in reality, commuters usually make travel decisions based on their day-long schedules. In the literature to date only a few published papers have involved analysis of day-long commuting problems. For example, Zhang et al. (2008) proposed an integrated daily commuting model that linked the morning and evening trips via choice of parking location. Recently, Gonzales and Daganzo (2013) incorporated mode choice in the combined morning and evening commute problem. More recently, Daganzo (2013) has further examined the day-long problem by considering two modes (auto and transit) and their distributed demand. However, the day-long commuting models developed in these studies have adopted the trip-based modeling approach, which means that the time-use decisions of commuters and the effects of flexibility in their activity scheduling cannot be properly addressed.

Zhang et al. (2005) presented a day-long activity-travel scheduling model to address commuters' time allocations among activities and travel during a day. Their model connected the morning and evening commutes via work duration. However, their paper did not examine the analytical properties of their proposed model. Recently, Jenelius et al. (2011) and Jenelius (2012) extended the Zhang et al. (2005) model to determine the values of travel-time savings and travel-time variability in both deterministic and stochastic environments. However, strong assumptions (e.g., no traffic congestion at the bottleneck) were made for derivation of some analytical properties of this model. In addition, none of these researchers (Zhang et al., Jenelius et al. or Jenelius) have considered the effects of schedule delays associated with work activities (which are usually mandatory activities). Recently, Ettema et al. (2007) showed that schedule delays for work activities play an important role in the commuters' scheduling of daily activities and travel, and such delays should therefore be considered in an activity-based model.