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Modeling and managing morning commute with both household and individual travels

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ABSTRACT

This study investigates the morning commute problem with both household and individual travels, where the household travel is a shared ride of household (family) members. In particular, it considers the situation when a proportion of commuters have to drive their children to school first and then go to work (household travel). For household travel, departure time choice is a joint decision based on all household members' preferences. Unlike the standard bottleneck model, the rush-hour dynamic traffic pattern with mixed travelers (household travelers and individual travelers) varies with the numbers of individual travelers and households, as well as the schedule difference between school and work. Given the numbers of individual travelers and households, we show that by appropriately coordinating the schedules of work and school, the traffic congestion at the highway bottleneck can be relieved, and hence the total travel cost can be reduced. This is because, departure/arrival of individual and household travels can be separated by schedule coordination. System performance under schedule coordination is quantified in terms of the relative proportions of the two classes of travelers and is compared with the extreme case when the same desired arrival time applies to both schooling and working. Furthermore, the efficiency of work and school schedule coordination in reducing travel cost is bounded. This efficiency is also compared with that at the system optimum where queuing is fully eliminated and schedule delay cost is minimized (achieved by a joint scheme of first-best pricing and schedule coordination).

1. Introduction

Traffic congestion is pervasive in many metropolitan areas and is worsening throughout many countries. In the literature, understanding the dynamic traffic pattern and managing traffic congestion in the morning peak hour have been studied extensively by both transportation scientists and economists. Vickrey (1969) was the first to propose the bottleneck model to capture the traffic dynamics in the rush hour. In Vickrey's model, the congestion is modeled as a deterministic queue behind a bottleneck of fixed capacity. Travelers choose their departure times to minimize individual travel cost including travel delay cost and schedule delay cost. Based on this model, various issues have been studied, e.g., existence and uniqueness of user

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equilibrium solution at a single bottleneck (Smith, 1984; Daganzo, 1985; Lindsey, 2004); road pricing, tradable credits, and tradable permits to manage traffic congestion (Arnott et al., 1990; Laih, 1994; Xiao et al., 2012; Tian et al., 2013; Nie and Yin, 2013; Wada and Akamatsu, 2013); stochastic bottleneck capacity and travel demand (Arnott et al., 1999; Lindsey, 2009; Xiao et al., 2015); morning commute with heterogeneous travelers (Arnott et al., 1994; van den Berg and Verhoef, 2011; Liu and Nie, 2011; Liu et al., 2014b; Liu et al., 2015a; Liu et al., 2015c); integrated problem of parking and morning commute (Arnott et al., 1991; Zhang et al., 2008; Qian et al., 2011; Qian et al., 2012; Yang et al., 2013; Liu et al., 2014a; Xiao et al., 2016); capacity drop and/or hyper-congestion (Arnott, 2013; Liu et al., 2015b; Liu and Geroliminis, 2016); complementarity formulation or ordinary differential equation formulation (Ramadurai et al., 2010; Wu and Huang, 2015; Wang and Xu, 2016).

However, most of the previous studies focus on analyzing and managing the commuting problem with individual travelers only. Little attention has been paid to household travels. Different from individual trips, a household trip consists of the travels of all household members, i.e., shared ride of household members. Note that ride sharing is encouraged as the same number of travelers can be transported with less vehicles and drivers, and traffic congestion and environmental pollution can be reduced. Recently, de Palma et al. (2015) considered that individuals live as couples and value time at home more when together than when alone. They estimated the trip-time preference for married and unmarried men and women in the Greater Paris region. More recently, Jia et al. (2016) considered the equilibrium trip scheduling for households where each household travel group consists of one adult traveler and one child, and the adult traveler has to send the child to school first and then go to the workplace. For household travel, more than one member in the household will be involved in the departure time choice decision, i.e., all the members' preference of arrival times have to be considered (e.g., for work and for school).

In Jia et al. (2016), all travelers are assumed to be household travelers. This is reasonable as a first step to understand how household travel is different from individual travel in departure time choices. However, this is usually not the case in reality as there will be both household travelers and individual travelers. Therefore, not only the interactions among members within a household can affect departure time decisions and the traffic equilibrium, but also the interactions among household travelers and individual travelers (through sharing the same road network) can re-shape the dynamic traffic pattern in the morning peak. This study, by considering this more realistic case with mixed travelers, will help us better understand the impact of household travels. Indeed, the model presented in this paper incorporates that in Jia et al. (2016) as a special or extreme case, where the number of individual travelers equals zero (this has been specified in Section 3).

Specifically, we consider that there are two types of travels: individual travel and household travel. An individual travel consists of only one trip, i.e., going to the workplace (given that travelers have a desired arrival time for work). A typical household travel consists of two successive trips, i.e., dropping off the children at the school and then going to the workplace. In this case, there are two desired arrival times: desired arrival time at school and desired arrival time at work. For individual travel, travelers have no cost associated with the school, while the household travel will take into account the costs associated with both school and work. We firstly explore the dynamic equilibrium traffic pattern with both household and individual travels. Then we examine how to coordinate school schedule and work schedule in order to reduce the traffic congestion, and thus reduce the total travel cost. Also, we analyze the efficiency of schedule coordination (for work and school).

It is worth mentioning that the efficiency of schedule coordination depends on relative proportions of the two classes of travelers, and can be bounded. Note that there is a branch of studies looking into staggered work hours (e.g., Henderson, 1981; Yushimito et al., 2014; Shirmohammadi et al., 2015; Takayama, 2015). However, all of these studies focus on the coordination of work schedules for individuals. None of them involves household trips or school schedule. Besides, we found that total travel cost can decrease with the proportion of household travelers in the population (which can be counterintuitive as a larger number of households suggest a larger number of travelers in total). We also found that schedule delay cost does not always increase with the difference between the two desired arrival times (for work and school).

The remainder of the paper is organized as follows. Section 2 presents problem description and the cost formulations for both households and individual travelers. The dynamic traffic pattern at departure/arrival equilibrium with mixed travelers is discussed in Section 3. Section 4 analyzes the system performance under given numbers of different travelers and work and school schedules, and then evaluates and bounds the efficiency of coordinating work and school schedules in reducing total travel cost. Numerical illustration and verification are presented in Section 5. Section 6 concludes the paper.

2. Problem formulation

Consider a bottleneck-constrained highway connecting a residential area and a city center (workplace) as shown in Fig. 1. There is a school between home and workplace after the highway bottleneck. In the morning commute, there are two types of travelers: individual travelers and household travelers, which are described in the following.

Firstly, N_1 individual travelers have to drive to the city center to work, and their desired arrival time at the workplace is t_2^*. For these individual travelers, they will make a trade-off between the travel time cost related to queue length at the highway bottleneck and the schedule delay cost of arriving early or late at work.

Besides the N_1 individual travelers, there are travelers from N_2 households. For simplicity, it is assumed that there is one adult and one child per household (all of them are referred to as household travelers in this paper). While later in the paper we sometimes might use N_2 to refer to household travelers, the total number of household travelers is indeed $2 \cdot N_2$ (including both the adults and the children). The adult members in the households have to drop off their children at the