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Integrated planning of park-and-ride facilities and transit service

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ABSTRACT

This paper proposes an integrated planning framework to locate park-and-ride (P&R) facilities and optimize their capacities as well as transit service frequencies simultaneously. P&R users' route choice behavior is explicitly considered, and a link-based multimodal user equilibrium model is established. The optimal location and capacity of P&R facilities and transit service design problem is formulated as a mathematical program with complementarity constraints (MPCC), and a solution algorithm based on the active-set approach is developed to solve the optimal design problem effectively. A numerical example is employed to demonstrate that the optimal design shifts commuters from the automobile mode to transit and P&R modes and, hence improves the net social benefit dramatically.

1. Introduction

Increasing car ownership and use have caused severe traffic congestion in megacities around the world in recent decades (Song, 2013). Tremendous efforts have been made to alleviate congestion problems; one approach is to increase the ridership of public transportation by introducing park-and-ride (P&R) facilities (Hamsa et al., 2014; Islam et al., 2015). P&R describes an operation in which commuters, traveling by private vehicles, gather at a common site and transfer to public transportation (Noel, 1988). The operation allows commuters to use either the automobile or transit in the geographic area to which it is best suited. Private vehicles are used for the initial portion of the trip to a P&R facility located in a low-density suburban or urban fringe area, where (fixed-route) transit services are not justified, while transferring to transit allows commuters to avoid traffic congestion and high parking costs in reaching major activity centers (e.g., central business districts).

Since its first introduction in Detroit in the 1930s (Bullard and Christiansen, 1983), P&R has been recognized as an effective way to promote public transportation and reduce traffic externalities in urban areas (e.g., Bolger et al., 1992; Niblette and Palmer, 1993; Duncan and Cook, 2014). As an instrument for travel demand management, P&R is getting increasingly popular because of many advantages it offers. A number of studies (e.g., Flint, 1992; Bolger et al., 1992; Roberts et al., 1998) demonstrate that P&R facilities have successfully reduced congestion and other external impacts in the United Kingdom and North America. Travelers who choose P&R schemes may experience less travel costs as well as increased travel comfort, and transportation operators may also benefit from the provision of P&R services due to the reduction in inner-urban parking demand (Lam et al., 2001). P&R can also help reduce air pollution since it encourages people to use public transportation for at least part of their trips (Noel, 1988; Lam et al., 2001; Du and Wang, 2014).

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Various modeling analyses of P&R facilities can be found in the literature. Fernandez et al. (1994) adopted mode choice models to evaluate the demands for different travel modes, including P&R, and then applied user equilibrium (UE) models to decide the traffic flow on each link. Foo (1997) evaluated the application of P&R scheme in Singapore. Garcia and Marin (2002) focused on the capacity and pricing design of P&R facilities, assuming that the parking facilities were located beforehand. Li et al. (2007) developed a network equilibrium formulation to model P&R services in a multimodal transportation network with elastic demand. They found many factors that influence the efficiency of a P&R scheme, including the parking fare and parking capacity at P&R sites and in central urban areas, and also the frequency and fare of transit service. Liu et al. (2009) presented a continuum equilibrium model to analyze commuters' modal choice behaviors in a multimodal network with continuum P&R facilities along a travel corridor. Liu and Meng (2014) modeled the stochastic UE problem with a bus-based P&R system and congestion pricing in a multimodal network. Based on the questionnaire survey data from P&R users in Melbourne, Islam et al. (2015) investigated the mode change behavior of P&R users. They found that travel time and parking fare are the primary factors that affect commuters' mode choice behavior. Pineda et al. (2016) proposed an integrated stochastic equilibrium model to describe the flow distributions among car mode, bus mode and P&R mode. They also presented a solution algorithm based on the method of successive averages to solve for the equilibrium state.

Planning P&R facilities has become increasingly important because many countries have been investing more than ever in high-quality transit services. For example, the number of fixed-guideway transit options (e.g., commuter, heavy, and light rail systems) in the U.S. has almost tripled over the last three decades (APTA, 2013). Beijing spent $5.4 billion in its mass transit system in 2009, accounting for more than 50% of its total transportation infrastructure budget (Song, 2013). Furthermore, many states in the U.S. are actively deploying managed lanes coupled with express bus services in those lanes. For example, an 800-mile regional managed-lane network is planned in the San Francisco Bay Area, California. The network will serve a high volume of express buses, whose implementation cost is expected to be $3.4 billion between 2015 and 2035 (MTC, 2008). Well-planned and managed P&R facilities are critical to the success of such high-quality transit services.

Although the modeling analyses of P&R facilities have been extensively investigated (see, e.g., Duncan and Christensen, 2013; Chen et al., 2014), there is still a lack of theoretically sound guidance on where to locate these facilities, an important aspect of P&R planning. Some agencies have provided criteria for selecting P&R facility locations (see, e.g., Burns, 1979; Fradd and Duff, 1989; Spillar, 1997; AASHTO, 2004). Based on selected criteria, the Florida Department of Transportation (FDOT) has adopted an expert system to rank potential P&R sites (FDOT, 2012). Faghri et al. (2002) developed a hybrid knowledge-based expert system to locate P&R facilities. However, this approach often produces confusing and even contradictory suggestions because these criteria are primarily based on experiential evidence (Holguin-Veras et al., 2012). Studies have also been conducted to directly optimize the locations of P&R facilities. However, most of these existing methodologies have limitations to some extent. Some, including Horner and Groves (2007), Farhan and Murray (2008), and Aros-vera et al. (2013), did not consider how commuters react to the provision of P&R facilities. Fan et al. (2013) applied stochastic UE to capture user response, but the model cannot handle complex transit networks, such as those with common-line sections. Others, such as Sargious and Janarthanan (1983), Wang et al. (2004a,b), and Holguin-Veras et al. (2012), focused on highly simplified settings such as a linear city. On the other hand, the attractiveness of P&R services not only relies on strategically deployed P&R facilities but also on the transit service levels serving these P&R facilities. Indeed, in the San Francisco Bay Area, some P&R lots are oversubscribed while others are nearly empty, and travelers would rather drive to work than use a poorly located and served P&R lot (Shirgaokar and Deakin, 2005).

As P&R facilities should be carefully planned and integrated into a multimodal transportation system, a systems approach is needed to consider the interactions of multiple transportation modes and commuters' choice of mode, P&R lot, and travel route. The objective of this study is to develop a theoretically sound methodology for designing P&R facilities and determining transit service frequency simultaneously to promote public transportation and reduce traffic externalities in urban areas. The remainder of this paper is organized as follows. Section 2 presents the problem statement and describes feasible flow distributions across a multimodal network with P&R facilities. Section 3 formulates a UE model in the multimodal network. Section 4 proposes the optimal P&R facility and the transit service design problem. Section 5 investigates the solution algorithm, followed by a numerical example in Section 6. Lastly, Section 7 concludes the paper.

2. Problem statement

Consider a multimodal transportation network $G = (V, L)$, where V and L denote the sets of nodes and directed links, respectively. The link set consists of four mutually exclusive subsets, namely road link set, L_R, transit link set, L_T, boarding link set, L_P, and alighting link set, L_E. Road and transit links are physically separated and are connected by boarding and alighting links. P&R facilities are assumed to be located at the tail nodes of boarding links, called boarding nodes. Boarding nodes are also termed P&R candidate nodes. These two terms will be used interchangeably hereinafter. Fig. 1 shows an example of multimodal network in which four types of links are present.

Commuters have the flexibility to choose one of three travel modes available in this multimodal network, i.e., automobile, a, transit, t, and P&R modes, p. The set of available modes is denoted as M, and $M = \{a, t, p\}$. It is assumed that commuters' mode choices can be captured by a multinomial logit model. It is further assumed that users for any origin-destination (OD) pair have access to all three travel modes. On the other hand, the aggregate travel demand for each OD pair is assumed to be given and fixed.