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Remote park-and-ride network equilibrium model and its applications

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ABSTRACT

Existing park-and-ride (P&R) sites are usually located near a train/bus station where construction and operation costs are considerably high. Thus, this paper proposes a new P&R service mode, "Remote P&R (RPR)", where the car park locates in a suburban area with lower land value. Dedicated express bus service is used to connect this site and a nearby train station. To quantitatively evaluate the impacts of RPR on the network flows, a combined modal split and traffic assignment model (CMSTA) is developed, where a cross-nested logit (CNL) model is adopted to cope with the mode similarity. The problem is formulated as a convex programming model and solved by the Evans algorithm, and then extended to asymmetric path-based cases, where a variational inequality (VI) model is built and solved by a self-adaptive gradient projection (SAGP) algorithm. Taking the CMSTA as the lower level and multimodal stochastic system optimum (MSSO) as the objective, we further develop a mathematical programming model with equilibrium constraints (MPEC) for the optimal network design of RPR. Based on an origin-based reformulation of the MPEC model, an exact solution method based on the nonlinear valid inequalities (NVI) is applied. Numerical examples demonstrate that the RPR services can significantly influence network users' travel decisions, promote the usage of public transportation and mitigate traffic congestion in the congested area of metropolitan cities.

1. Introduction

Prompting the usage of public transport (bus, train and tram) has been regarded as a universal solution to the severe congestion in urban areas. The public transport systems in e.g., many Australian cities, however, are less attractive compared with other dense cities in Europe and Asia. The low passenger demand in the vast suburban areas gives rise to: (a) low bus frequency; (b) tortuous bus itinerary; (c) much longer trip time; (d) lack of door-to-door services. Thus, for the majority of commuters living away from the train lines, it is very inconvenient to take public transport, in contrast with driving. P&R therefore becomes an important scheme to prompt the public transport usage in Australian cities. It allows the commuters to drive from home, park their car in a dedicated P&R site, and then take public transport to city area or other town centers.

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P&R can be categorized into bus-based P&R and rail-based P&R, based on different "ride" components. Most of the bus-based P&R is commonly adopted in small cities in US and UK with no developed rail system, where a dedicated express bus line is used for the P&R (Duncan, 2010 and Meek et al., 2008). In a trainpolitan area with an advanced rail system, rail-based P&R is more superior to bus-based P&R, due to the faster speed, higher level of safety and comfortability of rail system. Also, compared with bus-based P&R, the rail-based system is independent of traffic flows, thus its travel time is more accurate and stable. The existing P&R services in most Australian cities are also rail-based. Hence, this paper focuses on rail-based P&R network design problem.

Despite the convenience to the commuters, providing more parking spaces beside the train stations is usually not considered as transit-oriented-development (TOD). In addition, train stations are usually located in town centers, where the land value is relatively high, thus largely increasing the construction cost of P&R services. Thus, in this paper, we propose and focus on a new concept of P&R: site the P&R in undeveloped areas with low land value, and use dedicated express bus services to connect the P&R site to the train stations. This sort of P&R scheme is termed as "Remote P&R" (RPR) or "rail-based P&R with feeder bus services". Compared with the existing P&R systems, RPR provides a more general service framework where the car parks do not have to be close to a train station. With sufficient parking spaces and rapid feeder bus services, the travel impedance would be further reduced which results in an essentially different travelling behavior of the network users. Meanwhile, the redistribution of network flows on the network allows the transportation authorities to re-balance the flow distribution, promote the usage of public transport, alleviate traffic congestion in urban areas and reduce other adverse external effects of pure auto mode.

Previous studies revealed that the P&R scheme should be planned systemically, because it may also encourage existing public transport riders to drive, due to the convenience provided to driving (Hamer, 2010). Hence, arbitrarily constructed RPR sites could attract more public transport riders to drive, rather than the desired outcome of prompting more drivers to ride. It could also increase the total driving distance per vehicle, and thus deteriorate the traffic congestion/pollution. Thus, a systematic study is necessary to properly determine the optimal location and capacity of RPR sites subject to a given budget limit, which is taken as the main objective of this paper.

1.1. Literature review

Most of the previous studies on P&R focus on the policy side. Bus-based P&R has been commonly implemented in many UK cities (Parkhurst, 1995, 2000 and Parkhurst and Richardson, 2002). According to the study of Meek et al. (2008) on the bus-based P&R in the UK, 50–71% of weekday P&R users reported the car as their previous mode of travel, suggesting that P&R does assist in reducing car use. Cairns (1998) and Dijk and Montalvo (2011) summarized the policy frames of P&R in European cities. Lam et al. (2001) studied a trial P&R scheme in Hong Kong and gave a guideline for the design of P&R systems in Eastern Asia. Duncan and Christensen (2013) pointed out that the station area characteristics are significant predictors of the light-rail based P&R in the US. P&R facilities tend to be built in suburban areas with cheaper land and lower population density. Hamer (2010) conducted a survey in Melbourne to assess the impacts of P&R on the modal split, which indicated that the proportion of former drivers could be higher than that recorded. Wiseman et al. (2012) investigated a newly established Adelaide Entertainment Centre P&R facility located in the inner suburb of Hindmarsh, and concluded that location of P&R station is an important factor which can influence the performance of P&R system. They suggested the needs for more studies in Australian cities to better understand the P&R systems.

Quantitative studies on the modeling of P&R are relatively sparse. An initial work was carried out by Fernandez et al. (1994), where a pseudo link was adopted to represent the transfer behavior of passengers in the P&R car parks. This work was later extended to the case of asymmetric link travel time functions by Garciá and Marıń (2005), and to the logit-based stochastic model by Li et al. (2007) and Lam et al. (2007). Kitthamkesorn et al. (2016) considered mode similarity and route similarity of the green travel modes, and further extended to the case of webit-based model (Kitthamkesorn and Chen, 2017). Some other studies focus on the P&R schemes in a linear corridor, e.g., Wang et al. (2004), Wang et al. (2004b), Liu et al. (2009), Wang and Du (2013) and Du and Wang (2014).

Liu and Meng (2014) provided a formulation for the bus-based P&R in a network with the congestion charge. Wang et al. (2014) studied the P&R schemes in dynamic transport networks. Pineda et al. (2016) proposed an integrated traffic-transit stochastic equilibrium model with park-and-ride facilities. Song et al. (2017) provided an integrated planning scheme of P&R facilities and transit service.

Network analysis of P&R schemes endogenously involves the modal split as well as traffic assignment. The abovementioned studies on network analysis, however, have not well captured a unique feature of P&R: it has heavy overlaps with other transport systems; the first-half of a P&R trip overlaps with the road network and the second-half coincides with the transit network. In view of these overlaps, the cross-nested logit (CNL) model is more suitable for the network analysis of P&R schemes. The CNL model was initially proposed by Vovsha (1997) for transport network modeling. However, this seminal study cannot be used directly for the P&R network flow analysis since it does not involve traffic assignment. We thus aim to provide a holistic study on the flow equilibrium of a transport network with RPR schemes. Based on the CNL model, a combined modal split and traffic assignment (CMSTA) modeling framework is built. The CMSTA problem is first formulated as an optimization model for the simplified link-based case and then modeled as a VI problem for the asymmetric path-based case. The CMSTA model is then taken as equilibrium constraints for the optimal planning (siting and capacity design) of the P&R scheme.