Transportation network design for maximizing flow-based accessibility

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One of the significant aims of transportation network design and management is to improve the service level of the network and the accessibility of individual trips in a certain period. By adopting a well-defined accessibility measure, this paper studies a new discrete network design problem for metropolitan areas, in which some concepts, including the accessible flow, travel time budget function and principles of user equilibrium and system optimization with travel time budgets, are proposed. Then, two deterministic bi-level programming models are firstly formulated to maximize the network accessible flow. The upper level focuses on choosing the potential links in the pre-specified candidate set, and the lower level assigns all the flows to the super network with principles of user equilibrium or system optimization with travel time budgets. Moreover, to handle uncertain potential demands in reality, the problem of interest is further formulated as two-stage stochastic programming models. To solve these proposed models, efficient heuristic algorithms are designed on the basis of probability search algorithm, Frank–Wolfe algorithm and Monte Carlo simulation method. Finally, two sets of numerical experiments in the Sioux Falls network and San Diego freeway network, are executed to test and analyze the rationality and efficiency of the proposed approaches.

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1. Introduction

Transportation network design problem (TNDP) is an important component of traffic and transportation planning, and accessibility measure is a significant indicator for evaluating the quality of transportation networks. Up to now, these two issues have been extensively studied in the field of transportation sciences during the past several decades, because the related problems are highly complicated, theoretically interesting, practically significant and multidisciplinary (Abdulaal and Leblanc, 1979; Magnanti and Wong, 1984; Gao et al., 2004; Morris et al., 1979; Scheurer and Curtis, 2007; Farahani et al., 2013). In the literature, however, very few researchers have focused on TNDP models with the consideration of accessibility measure, due to the shortage of appropriate mathematical methods for addressing accessibility and its measurement. Tong et al. (2015) pointed out that urban transportation planning for accessibility is a challenge for the metropolitan planning organizations. The traditional approaches of TNDP, to our knowledge, focus on a transportation network configuration that optimizes network efficiency, being subject to the equilibrium constraints and pre-given construction budgets, in which the design costs and flow costs are usually taken into account.

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From a practical point of view, the studies on TNDP remain flourishing for a long time, because the travel demand is gradually enhanced due to the increasing population which exceeds the existing capacity of transportation infrastructure systems, and meanwhile spatial and financial resources of a city are limited. Since the purpose of TNDP aims to satisfy the potential demands as many as possible, it in essence reflects the characteristics of network accessibility. Practically, although the diversities exist in understanding accessibility for different decision-makers, its underlying meaning is typically related to the travel convenience between different origin-destination (OD) pairs in the considered network. In this sense, the network accessibility implies a significant factor for the travel process, i.e., travel time budget, which is associated with not only the spacial convenience but also the temporal convenience. To well-describe this concept, this study proposes the definition of accessible metropolitan areas through embedding the travel time budgets. Note that, it should be a significant topic for the real-world applications, since some potential travelers would like to cancel their trips because the actual travel time is probably beyond their anticipations (Liu and Zhou, 2016). Thus, jointly considering potential traveler demands, accessibility and reconfiguration of the transportation network, this study intends to maximize the total accessible flow so as to improve the service quality of the transportation network in metropolitan areas. Moreover, the relevant results can also provide an effective evaluation of service level in the newly designed network though measuring the total accessible flow with the consideration of travel time budgets. The following discussion explicitly addresses this issue.

1.1. Literature review

In the literature, a variety of studies have focused on the TNDP from different perspectives in the past decades. For clarity, we explicitly address the existing studies according to their individual characteristics. (1) Considering different network features and functions, the TNDP can be categorized into the road network design problem (RNDP) and service network design problem (SNDP). The RNDP aims to determine the optimal configuration of the urban network elements (topologies and capacities) with respect to distinctive evaluation criteria. Given an existing urban network, this problem intends to find the optimal configuration of the road network in terms of link directions, link capacities, parking spaces, and signals at the junctions (Cantarella and Vitetta, 2006; Szeto et al., 2013; Hosseininasab and Shetab-Boushehri, 2015). The SNDP, also called transit (including bus, metro and railway) network design problem, is to determine the station locations, route alignments, frequencies and ticket prices of public transit lines to serve the passenger demands between specific OD pairs (Fan and Machemehl, 2006; Yan et al., 2013; An and Lo, 2016; Liu and Zhou, 2016; Cancela et al., 2015). (2) Considering the continuity/discontinuity of the involved decision variables, the TNDP can be categorized into the continuous network design problem (CNDP), discrete network design problem (NDP) and mixed network design problem (MNDP). The CNDP aims to measure the performance of the existing network by determining additional capacity expansions of a subset of existing links, for instance, improving road conditions, polishing up road grades, reducing headway of a transit line, etc. (Abdulaal and Leblanc, 1979; Gao et al., 2004; Chiou, 2005; Liu and Wang, 2015), and the NDP is to optimize the network structure by adding new road sections or opening new transit lines to an existing network (LeBlanc, 1979; Poorzahedy and Turnquist, 1982; Gao et al., 2005; Wang et al., 2013; Hosseininasab and Shetab-Boushehri, 2015). Additionally, the MNDP simultaneously considers both CNDP and NDP in a network (Sun et al., 2009; Luathep et al., 2011). (3) Considering the certainty/uncertainty of demands, the TNDP can be categorized into the transportation network design problem with demand certainty (TNDP-C) and transportation network design problem with demand uncertainty (TNDP-U) (Bian et al., 2009; Wu et al., 2012; An and Lo, 2015; Chiou, 2016; An and Lo, 2016). What’s more, focusing on simultaneously optimizing the road network expansion scheme and bus network design scheme in an integrated manner, the multi-modal network design problem (MMNNDP) is attracting more and more attention recently (Zhang et al., 2014; Brands and Berkum, 2014).

From a systemic viewpoint, the process of transportation network design can be regarded as a hierarchical process which reflects interactions between decision makers and users. By supplying transportation infrastructures and facilities, the former attempts to influence the latter’s travel choices. In this sense, TNDP typically can be treated as a leader-follower game problem. In the literature, most transportation network design problems have been effectively described as bi-level programming models, where the upper level decides which links or lines and how much capacity should be constructed, and the lower level is a traffic assignment (trip behavior) model corresponding to the network conditions in response to the upper level decision (Chiou, 2005; Wang et al., 2013; Szeto et al., 2013; Chiou, 2016). Due to the intrinsic complexity of bi-level formulation, the TNDP has been recognized as one of the most difficult and challenging problems for global optimality (Magnanti and Wong, 1984; Gao et al., 2005). For this reason, some researchers attempted to reformulate TNDP as the single-level programming problem (Li et al., 2012; Wang et al., 2013; Farvaresh and Sepehri, 2011; An and Lo, 2016; Liu and Zhou, 2016).

In addition, it follows from the recent studies that the objective function of this problem gradually changes from various costs or utilities to land use, environment or equity, etc. For instance, Meng and Yang (2002) considered a phenomenon that some travelers could not get any benefit from the network design project, and then examined the benefit distribution among the network users and the resulting equity associated with the continuous network design problem. Camporeale et al. (2017) considered an SNDP of making transit service equitable from a geographical and social point of view, and attempted to incorporate both horizontal and vertical equity in the planning stage of a new public transportation system. Caggiani et al. (2017) handled an equity-based RNDP as a fuzzy programming problem. Assuming that the planner was environment-conscious and tried to minimize health-damage cost due to vehicular emissions along with total system
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