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Pareto-improving transportation network design and ownership regimes

Zhijia Tan[a,*], Hai Yang[b], Wei Tan[a], Zhichun Li[a]

[a] School of Management, Huazhong University of Science and Technology, 1037 Luoyu Road, Wuhan, PR China
[b] Department of Civil and Environmental Engineering, The Hong Kong University of Science and Technology, Clear Water Bay, Kowloon, Hong Kong, PR China

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ABSTRACT

Private provision of public roads signifies co-existence of free, public-tolled and private-tolled roads. This paper investigates the Pareto-improving transportation network design problem under various ownership regimes by allowing joint choice of road pricing and capacity enhancement on free links. The problem of interest is formulated as a bi-objective mathematical programming model that considers the travel cost of road users in each origin-destination pair and the investment return of the whole network. The non-dominated Pareto-improving solutions of toll and/or capacity enhancement schemes are sought for achieving a win-win situation. A sufficient condition is provided for the existence of the non-dominated Pareto-improving schemes and then the properties of those schemes are analyzed. It is found that, under some mild assumptions, the optimal capacity enhancement is uniquely determined by the link flow under any non-dominated Pareto-improving scheme. As a result, the joint road pricing and capacity enhancement problem reduces to a bi-objective second-best road pricing problem. A revenue distribution mechanism with return rate guarantee is proposed to implement the non-dominated Pareto-improving schemes.

1. Introduction

Network design problems (NDPs) have been witnessed with the development of a vast and growing body of research focused on formulations and solution methods since the pioneering work of Abdulaal and LeBlanc (1979). The NDPs include (i) discrete network design problems (DNDPs), (ii) continuous network design problems (CNDPs) and (iii) mixed network design problems (MNDPs). The DNDPs deal with addition of new links to the existing transportation network; the CNDPs address capacity enhancements of existing links in the network; and the MNDPs are a mixture of (i) and (ii) (for a comprehensive review, see Yang and Bell, 1998; Meng et al., 2001, and the references therein). The objective of the NDPs is usually to make an optimal investment decision in order to minimize total user travel cost or maximize social surplus in the network, while accounting for route choice behavior of network users (Meng et al., 2001; Chiou, 2005).

Most of previous related models assume the availability of full information on demand/supply sides, implying ignorance of the impacts of demand/supply uncertainty. Using the expected demand could lead to an overestimated and erroneous choice of improvement (Waller et al., 2001). Two methods are witnessed in extending the deterministic NDPs to incorporate

* Corresponding author. Tel.: 13871203424.
E-mail address: zjatan@hust.edu.cn (Z. Tan).

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demand uncertainty: one is the stochastic programming method that often assumes a distribution of random future demand or inflation (Lo and Tung, 2003; Sumalee et al., 2009) and the other is the robust optimization method that achieves the insensitive solution to the demand uncertainty (Luo et al., 2009; Yin et al., 2009). For a given distribution, the reliability issue is addressed in the NDP to obtain a design with low failure probability. However, the strong assumption of a known cumulative distribution of demand limits is practically restrictive. Robust optimization is needed to control the risk of demand uncertainty. By introducing the uncertainty into the NDPs, several researchers considered multiple design objectives. Sharma et al. (2009) proposed a bi-objective programming model to minimize the expectation and variance of total system travel time. Yin et al. (2009) introduced several optimization models to consider the multiple objectives of the NDPs. Chen and Xu (2012) and Xu et al. (2013) adopted the goal programming approach to solve the NDPs with multiple objectives and demand uncertainty. The approach is adopted by Yin et al. (2014) to investigate the joint pricing and capacity investment problem with multicriteria including cost recovery, service quality, environment and equity. Chen et al. (2011) conducted a systematically literature review on the NDPs under uncertainty.

Equity issue and dynamic characteristics of traffic demand are also two important extensions of the NDPs. Note that the equilibrium origin-destination (OD) travel costs for some OD pairs may increase after implementing the optimal design scheme, thereby inflicting a negative impact on some users. Meng and Yang (2002) and Chen and Yang (2004) addressed the equity issue in the NDPs and imposed additional constraints on the maximal increase in OD travel costs. The constraints to a certain extent guarantee that more users can be more or less beneficial from the NDP scheme. By incorporating the dynamic stochasticity and elasticity of demand, Ukkusuri and Patil (2009) introduced a stochastic programming model to capture the flexible NDPs. The dynamic NDPs were also investigated by Lo and Tung (2003) and Szeto and Lo (2005). Recently, Tong et al. (2015) addressed the NDP to maximize the system-wide transportation accessibility by constructing a time-dependent space-time network.

Being one of the most acute challenges for the NDPs, development of solution algorithms attracted a lot of attention particularly in recent years. Wang and Lo (2010) adopted a linearization method to transform the non-linear, non-convex CNDPs into a mixed-integer programming problem and used the commercial optimization package CPLEX-8.0-MIP to find the global optimum. Luathep et al. (2011) proposed the global optimization method for the MNDPs. Wang et al. (2013) proposed two global optimization methods for the DNDPs by taking advantage of the relationship between the user equilibrium and social optimum. Other variants of the solution algorithms are proposed by Gao et al. (2005), Poorzahedy and Rouhani (2007), Li et al. (2012), Farvaresh and Sepehri (2013), Liu and Wang (2015) and Wang et al. (2015). Fontaine and Minner (2014) proposed a Benders decomposition algorithm for linear bi-level problems with binary leader and continuous follower variables under the partial cooperation assumption. Their method can be useful to the discrete network design problems.

Political issues and private participation in the transportation facilities investment are seldom addressed in the NDPs. Because of the shortage of public funds for highway network improvements, the authorities would like to confer the private investors to operate the state-owned roads. Therefore, from a practical point of view, some roadway links are owned by the private sectors, a mixed ownership regime thus emerges in the transportation network, where both private and public toll roads co-exist, together with the free state-owned roads. Under such a mixed ownership regime, introducing some new links or expanding the capacities of some existing links will likely induce losses of some private operators of existing roads. An example is the concession contract of the California Orange County Route 91, a public-private-partnership (PPP) highway project, which set a “non-compete clause” preventing any capacity expansion of the free alternative till year 2035. With the exacerbating congestion, the government agency had to buy back the road in $207 million (the initial investment is $130 million) (Engel et al., 2013). Another example is the French motorway network. As shown in Fig. 1, the motorway network is operated by sixteen private companies depicted with different colors and the gray ones are free roads managed by the government. In the presence of various ownership regimes, the NDP goes much beyond a purely technical problem. Tan (2012) investigated the selection of the capacity and toll charge for an “add-on” road competing with an existing alternative under various ownership regimes. He proved that the ownership regimes have significant effects on the optimal decision of the “add-on” toll road. Recently, Watling et al. (2015) investigated the cordon toll competition between two local authorities who control their own local transportation networks. Wang and Zhang (2015) studied the traditional transportation network design problem by considering that the network is controlled by multiple local transportation authorities.

We term the NDPs with various private companies operating the various parts of the network as the transportation network design problem under various ownership regimes. For a given transportation network and the ownership regime of each link, the objective of the government is to maximize the total social benefit (i.e. user travel cost saving plus the investors’ surplus) by finding the optimal link subset from the free state-owned links, and selecting the corresponding link toll and/or capacity enhancement. Note that the toll road scheme may not be profitable to all private investors including the incumbent investors and new entrants. We assume that the investors are willing to accept the project whenever their current interest is not worse off and the government can adopt the cross-market subsidization to re-distribute the surplus among all investors. To address the equity issue among road users, we assume that all road users will be happy if their travel cost (travel time delay plus toll charge if any) after implementing the new NDP scheme is not higher than before. Therefore, to guarantee the success of the capacity enhancement scheme, the interests of both the investors (incumbent investors and the new entrants) and the road users must not be affected negatively. Namely, the solution of the NDP under various ownership regime requires being Pareto-improving.

The paper is organized as follows. In the next section, we first propose the mathematical formulations to characterize the NDP under various ownership regimes and elaborate some basic assumptions. The definition of the non-dominated