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An integrated model for road capacity choice and cordon toll pricing

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ABSTRACT

In this paper, an analytical model is proposed to address road capacity choice and cordon toll pricing issues for an urban transportation corridor. In the proposed model, the road capacity, toll location and level are considered as decision variables, and the effects of self-financing and subsidy constraints on these variables are explored. It has been shown in the numerical studies that the self-financing requirement can lead to a decreased social welfare, and subsidies in certain ranges are welfare-improving. Results also show that subsidy increments yield disproportionately smaller welfare improvements, which is a sign of low efficiency.

1. Introduction

Many developing countries including China have been experiencing rapid urbanization and motorization. In 2005, there were a total number of 30 million motorized vehicles registered in China. This number rose to 219 million in 2015, increasing sevenfold during 10 years (NBSC, 2005–2015). The growth in the number of vehicles in many densely populated Chinese cities has been even faster. For instance, in Beijing, the number of vehicles increased to 7.2 million by the end of 2015, an eightfold increase during the same 10-year period. In Shanghai, the number of vehicles increased around 7.8-fold up to 4.30 million. Meanwhile, the annual growth rate of the total length of Chinese road network (in kilometers) was about 8% during 2005–2015. This imbalance of supply and demand has led to severe traffic congestion and emissions in many Chinese metropolitans. Although several demand management methods are adopted in Beijing for limiting the auto use and ownership, e.g., the end-number license plate policy and license plate lottery, Beijing has still been experiencing heavy congestion and pollution. Huge economic costs due to the congestion and environmental impacts are incurred.

Various policies to curb traffic congestion have been proposed over the years. The traditional response is to expand road capacity by building new roads, while capacity expansion might further induces excessive travel. The other way is to reduce travel demand by discouraging travel, imposing toll charges on vehicles. Cordon toll pricing schemes are widely acknowledged as effective methods for addressing traffic congestion and the associated environmental issues because of its potential to internalize some of the congestion and environmental externalities (Li, Lam, & Wong, 2012). Under congestion pricing schemes, a toll is charged to each vehicle passing through a specified cordon. Real-world applications include those pricing schemes adopted in Singapore, Edinburgh, Hong Kong, Oslo, and Bergen (Anas & Lindsey, 2011; Laird, Nash, & Shepherd, 2007; Rouwendal & Verhoef, 2006; Zhang & Yang, 2004).

After reviewing the existing studies on the cordon toll pricing problem, we find that (1) the road capacity is mostly assumed to be a fixed parameter rather than a decision variable; (2) the effect of financial constraints on the cordon toll pricing problem is unclear; (3) the environment effect of traffic emissions on the cordon toll pricing is largely unconsidered. Therefore, we seek to propose an integrated optimization model to jointly determine the road capacity, cordon location and toll level, for a commuter corridor, with considerations of various financial situations and the emission impact.

The remainder of this paper is organized as follows. Section 2 provides a literature review of existing cordon toll pricing studies. Section 3 presents the key components of the proposed model, including basic assumptions, and various function definitions.

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Section 4 provides three optimization models and also discusses the solution method. Case studies in Section 5 are used to illustrate the applications of the proposed models. Section 6 concludes the paper with major findings and presents some recommendations for future studies.

2. Literature review

Mun, Konishi, and Yoshikawa (2003) offered an analysis on the features of an optimal cordon toll pricing scheme in the economics literature, together with Lindsney and Verhoef (2001), De Lara, De Palma, Kilani, and Piperno (2013), Fujishima (2011), and Li, Wang, Lam, Sumalee, and Choi (2014). Based on a number of studies on cordon toll pricing issues, two groups of modeling methods have been adopted in the literature: the discrete network modeling approach and the continuum modeling approach. The discrete network modeling approach is useful for practical applications (Akiyama & Okushima, 2006; Rouwendal & Verhoef, 2006; Shepherd & Sumalee, 2004; Sumalee, 2004, 2007; Zhang & Yang, 2004), because it can capture site-specific characteristics. The continuum modeling approach can address the properties of the urban system analytically and lead to a general conclusion with regard to urban policies. This method has also been widely used in previous studies about road toll pricing issues (Chu & Tsai, 2008; Ho, Wong, Yang, & Loo, 2005, 2013; Li et al., 2014:; Mun et al., 2003, 2005).

Table 1 summarizes a few studies in terms of what decisions are considered, and whether financial constraints or environment effects are considered. From these studies, we can find that in most studies (1) the road capacity is treated as a pre-specified and fixed parameter rather than a decision variable; (2) financial constraints, e.g., self-financing or subsidy requirements, are not considered; (3) the environment effect is usually not incorporated.

Some researches try to account for the road capacity choice in their models. Newbery (1989) proved that with constant returns to scale in construction and use, the balance, together with the interest of the capital cost, will be recovered by congestion charges. Arnott and Kraus (1995) investigated under what circumstances the first-best pricing and investment rules apply when both the time variation of the congestion charge is constrained. Verhoef and Rouwendal (2004) explored the relations between pricing, capacity choice and financing in transportation networks. Chu and Tsai (2008) studied a special case where the government is assumed to have built a new elevated road on a corridor to reduce the traffic congestion. Tan (2012) studied how to select the toll and capacity level for a new toll road added onto an existing network with a single link. There are no studies jointly optimizing the toll location, toll level and road capacity, particularly in a way of analytical solution.

The effect of financial constraints has not been systematically analyzed in the cordon toll pricing studies. An optimal design from solving an optimization problem without financial constraints might be financially infeasible at all. For instance, when the toll revenue cannot cover the road capacity provision cost, a deficit is unavoidable. Therefore, financial constraints, such as self-financing, should be considered. In transportation economics, the self-financing theorem by Mohring and Harwitz (1962) establishes a significant relation between demand management and capacity policies, the revenue from optimal congestion pricing will be sufficient for financing the cost associated with optimal capacity supply. Lindsey (2009a) illustrated that under most plausible assumptions, capacity is found to be smaller with tolling than without tolling because this decreases the scope for further cost reductions from greater capacity. Lindsey (2009b) examined the effects of demand and capacity uncertainties on the cost recovery theorem for highway travel. Lindsey (2012) reviewed the theory of congestion pricing and the relationship between optimal congestion tolls and optimal road capacity. Verhoef and Mohring (2009) found that potential erroneous interpretations can be resulted from the self-financing theorem. In Yang and Meng (2000), the selection of toll and capacity for a private highway in a general road network was considered and the profitability and social welfare gain was also investigated. Yang and Meng (2002) later showed that the self-financing results holds for a network as a whole under the condition that each link cost function is homogeneous of degree zero and there are constant returns to scale in roadway construction.

In the area of public transit, Chang and Schonfeld (1993) studied various financial situations (i.e., unconstrained, break-even, and subsidy case) under the variable demand assumption and notably reported that in the vicinity of the maximum welfare solution, the welfare is relatively flat with respect to subsidies. Jara-Díaz and Gschwender (2009) also analyzed the effect of financial constraint under a fixed demand assumption. They found that an active self-financing constraint leads to socially inferior solutions. Nonetheless, Chang and Schonfeld (1993) and Jara-Díaz and Gschwender (2009) were focused on the public transit field. Instead of imposing a self-financing constraint, potential monetary transfers, e.g., subsidy, can be used to fill the deficit (Sun & Schonfeld, 2015; Zhou, Kim, Schonfeld, & Kim, 2008).

Some relevant studies in road franchising include Tan, Yang, and Guo (2010), Tan and Yang (2012), and Shi, Yin, and Guo (2016). Tan et al. (2010) included a zero-profit constraint in the build-operate-transfer (BOT) contract design and several types of government regulations, such as rate-of-return regulation and price-cap return were also considered. In Tan and Yang (2012), demand uncertainty was considered and in Shi et al. (2016), cost uncertainty was modelled.

In view of these concerns, in this paper we propose an integrated optimization model for the road capacity choice and cordon toll pricing for an urban corridor, with consideration of emissions effects. The main contributions are twofold, listed as follows:

1) A mathematical model to simultaneously investigate road capacity choice and cordon toll location/pricing for the maximization of the total social welfare is proposed. Instead of assuming the road capacity to be exogenously given, we seek to

Table 1
Key features considered in cordon toll pricing research.

Study	Decision Variables	Self-Financing Constraint	Environmental Effect
Mun et al. (2003)	Toll location and toll level	No	No
Mun et al. (2005)	Toll location and toll level	No	No
Ho et al. (2005)	Toll level	No	No
Ho et al. (2013)	Toll level	No	No
Li et al. (2014)	Toll location and toll level	No	Yes
This paper	Road capacity, toll location, and toll level	Yes	Yes

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