



Joint implementation of tradable credit and road pricing in public-private partnership networks considering mixed equilibrium behaviors

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ABSTRACT

This paper investigates joint road charging schemes in a public-private partnership (PPP) network by simultaneously taking into account Cournot-Nash (CN) players and user equilibrium (UE) players. Each joint scheme comprises a tradable credit plan for public roads and a regular tolling plan for private roads. We show that, under UE-CN mixed equilibrium, there exist anonymous nonnegative joint schemes that can support a system optimum link flow pattern. By using preemptive approach, we further design three bi-objective optimization models with hybrid implementation of tradable credit and road pricing. Numerical examples demonstrate that the proposed methods are effective in managing PPP networks.

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1. Introduction

In recent decades, we have witnessed a booming development of road franchising through build-operation-transfer (BOT) contracts, particularly in developing countries. For example, the highway mileage of constructed BOT roads in Sichuan, one province in China, has grown up to 1700 km in 2014 and will reach more than 3000 km in five years according to government's investment planning report. In 2015, the Ministry of Transport of P.R. China has enacted that the existing BOT road franchising projects could be issued a full 30-year concession period regardless of ex ante operation period. The popularity of BOT franchising projects in road construction and operation is attributed to the BOT merits of improving social efficiency, enhancing private financing and reducing the investment risk to government agency (Tan et al., 2010). Apart from BOT roads, there still exist some public roads in the real transportation networks. In general, public roads are managed by government authorities. Therefore, transportation networks are often operated in the form of public-private partnership (PPP). At the PPP operation and/or management levels, the private BOT operator focuses on financial revenue or deficit; whereas, the transportation authorities pay more attention to mitigate traffic congestion in the networks. For example, Kang et al. (2013) formulated a three-stage game auction model to investigate royalty bargaining of PPP projects and applied the model to an underground railway station project in Taiwan.

Given the fact that congestion alleviation by adding more capacities is often offset by induced travel demands (He et al., 2013), the importance and value of market-driven instruments have been appreciated and emphasized by various stakeholders, including transport practitioners, scientists and the public. Two categories of market-driven instruments, namely monetary-based congestion pricing scheme and quantity-based tradable credit scheme, are suitable for PPP networks,

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and there are various papers working on either category of the instruments. Since the pioneer work of Pigou (1920), the theory of road congestion pricing has attracted a lot of attentions in the past century. The marginal-cost congestion pricing has been extended to incorporate various external conditions in a complex transport system, for example, tolling design considering social equity (e.g., Yang and Zhang, 2002), optimal pricing scheme with uncertain demand (e.g., Sumalee and Xu, 2011), cordon-based congestion pricing (e.g., Zhang and Yang, 2004; Liu et al., 2014) and road pricing models with heterogeneous users (e.g., Zhang et al., 2008; Meng et al., 2012). Interested readers are referred to Yang and Huang (2005), Tsekeris and Voß (2009) and de Palma and Lindsey (2011) for comprehensive reviews and discussions on recent advances. However, the above road congestion pricing studies only considered the interest of transport administrator, who desires to mitigate the network congestion, but failed to take into account the interest of the other PPP player, BOT operator, who wishes to ensure certain revenue. This need of revenue has enlightened interests to balance possible conflicting objectives between transportation authority and private BOT operators (see Xiao et al., 2007; Wang et al., 2011; Wu et al., 2011 for instance).

On the other side, quantity-based tradable credit scheme efficiently regulates travel demands by distributing tradable mobility credits, where travelers need to pay required credits to access transportation facilities. In the spirit of credit application in pollution control (e.g., Malueg, 1990; Nagurney and Dhandu, 2000), a few transport researchers have advocated to consider credit scheme in managing road congestion externality (e.g., Verhoef et al., 1997). It is believed that tradable credit scheme holds a few merits compared to congestion pricing method, such as low public objection for implementation (fair social welfare allocation) and high flexibility of credit distribution. Recently, Yang and Wang (2011) put forward a formalized framework of tradable credit scheme to manage transportation network mobility. Subsequently, a series of related extensions are made to account for various traffic scenarios or conditions, including user heterogeneity (Wang et al., 2012; Tian et al., 2013), impact of transaction costs (Nie, 2012; He et al., 2013), income effect (Wu et al., 2012), demand and/or supply uncertainty (Shirmohammadi et al., 2013), day-to-day dynamic evolution of credit price and traffic flows (Garcia et al., 2012; Ye and Yang, 2013; Wada and Akamatsu, 2013), user mixed behaviors (He et al., 2013), travelers' loss aversion (Bao et al., 2014), integration of network design (Wang et al., 2014) and multi-period tradable credit scheme with/without transfer fee over periods (Miralinaghi and Peeta, 2016). Readers can find more information of recent developments on tradable credit schemes in Fan and Jiang (2013) and Grant-Muller and Xu (2014).

As mentioned above, a PPP network typically comprises public roads and franchising private roads. For public roads, tradable credit scheme is more applicable due to its merits, for example, alleviating travelers' participation obstacles, enhancing the freedom of credit usage for travelers, ensuring equal and flexible social welfare redistributions by trading, and reducing political resistance resulted from excess government intervention (Yang and Wang, 2011). For private roads, traditional pricing is still more appealing since revenue should be collected to finance the construction and maintenance costs of road infrastructures for private operators. In this study, we investigate the PPP network management problem from the perspective of the government, who has a principal target of pursuing system optimum (SO) that total travel time on the network is minimized. In order to achieve this objective, the government needs to determine the toll levels on private roads as well as the distribution of tradable credits on public roads. To make the system more practical, some requirements of the BOT firms have to be satisfied, such as minimal revenue requirement and compensation condition. For example, the government always allows an acceptable profit for the BOT firm when designing BOT contracts (Guo and Yang, 2009; Tan and Yang, 2012; Wu et al., 2011). In some cases, the government may even subsidize BOT firms to cover their deficits, although some constraints have been incorporated into the joint road charging design to ensure a minimal toll revenue. Under this circumstance, the government could ideally manage the PPP network through a hybrid implementation scheme (i.e., joint road charging management). More specifically, the government, on one hand, distributes credits and determines link-based credit charging plan on public roads; and on the other hand, designs a toll pricing plan exclusively on private roads.

The benefit of implementing a joint road charging scheme is worth noting. To satisfy the monetary need of private operators, the government has sufficient incentive to keep regular pricing for private roads. In addition, implementing differentiated charging schemes generates respective revenues for the government and BOT firm, avoiding potential dissensions on profit ownership and operating concession. Credit revenues would eventually be refunded to travelers; whereas toll revenues are retained by BOT firms unless concession period is expired. It further gives answers to the following two questions: (i) whether the government needs to subsidize the BOT firm, and (ii) how much is the compensation? This helps to contract appealing BOT agreements. With regard to practicability, in an Internet era, the sophisticated Electronic Toll Collection System coupling with advanced communication and license identification techniques could greatly enhance an extensive application of such joint charging schemes.

The joint road charging management would result in a win-win situation for the government and BOT firm. With a strong pricing power, the government may achieve his management target of system optimum, and meanwhile, has an opportunity to fulfill other design objectives, such as minimizing toll booths and the number of credits. For the BOT firm, although its pricing has to be regulated by the government, a sustainable operation can still be guaranteed through negotiated revenue requirements and compensation terms. Moreover, the BOT firm's operation risk is under control since financial deficit from unpredictable factors (e.g., demand uncertainty) could be alleviated or even avoided.

We then turn to travelers in PPP networks and their routing choice behaviors. An appropriate modeling of travelers' routing choice behaviors is very important for decision-makings. Previous studies often take classical Wardropian principles, either UE or SO principle, to characterize travelers' routing decisions (Yang and Zhang, 2008). However, such assumption is unrealistic since there are different groups of users, including large freight forwarders, consolidators and transit fleets as well as individual commuters (Harker, 1988). In the spirit of Harker (1988) and Yang and Zhang (2008), we consider

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