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Congestion tolling - dollars versus tokens: A comparative analysis

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ABSTRACT

The case for some form of congestion tolling has long been made given the extent of traffic congestion in most urban transportation networks. However, there is little consensus on whether this tolling should be in the form of dollars (traditional congestion pricing schemes or price regulation) or in the form of tokens (credit based mobility schemes or quantity regulation). Although the comparison of price and quantity regulation has received significant attention in the economics community, the literature is relatively sparse in the context of transportation systems. The two systems differ not only in terms of transaction costs but also in their efficiency in dealing with demand and capacity shocks, frequent in road transport systems. This difference has been explored by economists in market contexts but the possible parallel in transport systems has largely been overlooked. This paper develops a methodology to compare the performance of price and quantity instruments under uncertainty using a simple transportation network consisting of parallel highway routes and a public transport alternative. Tolls (in dollars or tokens) are differentiated across roads and the permits or tokens can be traded across roads at fixed rates. The demand for each route is determined by a logit mixture model and the supply consists of static congestion. The comparison is based on the optimum social welfare which is computed for each instrument by solving a non-convex optimization problem involving stochastic user equilibrium constraints. Equity considerations are also examined.

Numerical experiments across a wide range of demand/supply inputs lead us to the following insights. First, when the tolls in dollars and tokens can be fully adapted to demand and supply shocks (i.e. are day-to-day adaptive), both instruments are equivalent and attain the same optimum social welfare. Second, when the tolling system is not day-to-day adaptive and the supply of tokens is fixed, the quantity instrument performs better than the price instrument typically when the marginal external congestion function has a steeper slope than the demand function. Third, when the tolling system is non-adaptive, but the supply of tokens is day-to-day adaptive, the quantity instrument always outperforms the price instrument in terms of social welfare. Fourth, when the toll revenues and permits are dis-

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tributed uniformly, this has a positive equity effect but the quantity instrument is more equitable than the price instrument. In view of these results, we argue the case for quantity control in the presence of uncertainty and strongly convex congestion costs.

1. Introduction

The case for travel demand management through some form of tolling has been widely made in the literature given the large costs of traffic congestion to the commuter, economy and environment (see de Palma and Lindsey (2011) for a review). Tolling can be implemented though currency/dollars (traditional congestion pricing schemes which are a form of price regulation) or through tokens (tradable credit schemes or mobility permit systems which are a form of quantity regulation). Tolling through tokens is an appealing control instrument vis-à-vis tolling though dollars for several reasons: (1) it is revenue neutral, (2) implementation costs are low (Gao and Peh, 2016), (3) any desired equity distribution can be achieved through the initial token endowment, and (4) it provides the ability to directly control quantity. In view of these advantages, a natural question that arises is, which of the two instruments is superior in terms of social welfare? This paper attempts to answer this question.

Token or mobility permit systems come in different forms, but can, with the right technology, cope with complex route systems and variation within days. The literature on the use of mobility permits has been reviewed by Fan and Jiang (2013). They point to the many variants of tradable mobility permits: they can be per mile, per day, specific for one route or period within the day, bankable over days or limited to one day, traded via a central trading organism or not etc.

In the absence of uncertainty, transaction costs and revenue constraints, both systems perform equally well in terms of economic efficiency. The transportation system, however, is characterized by significant uncertainty and in this case, the two instruments perform differently. Demand is uncertain because of day-to-day, time-of-day and seasonal variations, special events, weather conditions, etc. Supply can be uncertain because of weather, accidents and incidents which affect road capacity and traffic dynamics. This is particularly important for road use which depends on demand and supply (capacity) at a specific time of day, such as the morning peak, when congestion is high. Intuitively, tolling through dollars (price regulation) fixes the access price but usage can vary strongly. In contrast, tolling through tokens (quantity regulation) fixes maximal usage but the trading price can vary strongly from day to day.

This paper is among the first to compare the efficiency properties of the price and quantity systems for a transportation system under uncertainty, and develops a methodology to compute optimal ex ante tolls in dollars and tokens for a system of parallel highways and a public transport alternative. Demand is characterized by a logit-mixture model and supply involves static congestion using BPR functions. The efficiency of the two instruments is compared in three configurations of the tolling system (adaptive tolls, non-adaptive tolls, non-adaptive tolls with adaptive token supply) and considers demand uncertainty, supply uncertainty and a combination of both types of uncertainty. Equity aspects are also examined.

The paper offers a rigorous analytical and computational framework which leads to the following insights: First, when the tolling system (either in dollars or tokens) is day-to-day adaptive, both instruments are equivalent. Second, when the tolling system is non-adaptive and the supply of tokens is fixed, neither instrument is consistently superior. In this case, when demand is uncertain, the steeper the marginal external congestion function compared to the slope of the demand function, the better will be the token system. When road capacity is uncertain, both systems perform equally well and the welfare losses are increasing in the range of capacity uncertainty. Further, when the level of demand and capacity are inversely correlated, the token system typically performs better. Third, when the tolls in dollars and tokens are non-adaptive, but the supply of tokens is day-to-day adaptive, the token system is always superior in terms of social welfare. In light of these findings and given the aforementioned advantages of tolling thorough tokens we argue the case for quantity control under uncertainty when the congestion costs are strongly convex.

The paper is divided into seven sections. Section 2 briefly reviews relevant literature. Section 3 introduces the basic demand and supply model. Section 4 compares the two instruments for the case when the tolls in dollars and tolls in tokens are day-to-day adaptive. Section 5 considers the setting where the tolling system is not day-to-day adaptive and the supply of tokens is fixed across days. Section 6 relaxes the assumption of a fixed token supply, compares the two instruments when the supply of tokens is day-to-day adaptive and also the equity effects of price and quantity regulation. Finally, Section 7 presents concluding remarks and some directions for future research.

2. Literature review

Congested roads are in the end a scarcity problem and this can be dealt with by either a price instrument, a quantity instrument or a combination of both. With a quantity control system, the number of tokens (mobility permits) to use a congested road is limited (and exogenously determined). In this case, the number of distributed tokens (and volume of car use) is given, but these tokens can be traded among the users. The equilibrium price of tokens is endogenous and clears