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The impact of user heterogeneity on road franchising

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ABSTRACT

A model is presented for analyzing Pareto-efficient build-operate-transfer toll road contracts. The formulation simultaneously allows maximizing social welfare and private profit when road users vary in their value-of-time (VOT). The failure rate and mean residual functions of the VOT distribution are used to characterize Pareto-efficient solutions. Service quality, measured in terms of the volume-to-capacity ratio, is shown to be better than, identical to, or lower than the socially optimal level depending on the curvature of the mean residual VOT function. The outcomes of various regulatory regimes are examined as well.

1. Introduction

Private provision of public roads through build-operate-transfer (BOT) contracts is increasing worldwide in both developed and developing countries. Previous studies on private roads have mainly focused on toll charges and capacity choices and their impacts on social welfare and profits (Yang and Huang, 2005; Lindsey, 2006; Small and Verhoef, 2007). A central result in the literature is the self-financing theorem established for first-best environments (Mohring and Harwitz, 1962; Verhoef and Mohring, 2009) which states that under certain conditions, an optimally designed and priced road should generate toll revenues just sufficient to cover its capital costs. Extensions of the relationship between congestion-toll revenues and road costs were made in a general network situation (Yang and Meng, 2002; Yang and Huang, 2005).

One important decision generally ignored in studies of BOT projects is the length of the concession. Only recently have Guo and Yang (2009a) conducted a preliminary study of concession length assuming deterministic demand and homogeneous users. They incorporated concession period, road capacity and toll charges in their analysis and explicitly considered traffic congestion and demand elasticity for unconstrained and profit-constrained, welfare-maximizing BOT contracts. They found that to maximize social welfare it is better to set the concession period as long as possible. Tan et al. (2010) generalized Guo and Yang's results and further investigated the Pareto-optimality of a BOT contract for maximizing both social welfare and private profit assuming full information about demand and costs. A few interesting and useful observations resulted. Under certain conditions, they found that service quality in terms of the volume-to-capacity ratio of the road is constant and that the concession length should be set to be the road's lifetime for any Pareto-efficient BOT contract including the social optimum and the monopoly solution. They proved that both price-cap and rate-of-return regulations result in inefficient outcomes, while demand and markup charge regulations lead to Pareto-optimal results.

The concept of value-of-time (VOT) plays a pivotal role in analyzing travelers' route choices, particularly in simulating travelers' responses to toll roads, as it describes how users trade off money against time in response to toll charges. Travelers value their travel time differently, depending on their income levels and their purposes for traveling. Certain American

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highways offer parallel free lanes to toll road users, allowing the users to choose according to the value they attach to travel time savings. State route 91 in California and Interstate 394 in Minnesota are two examples. However, the toll setting procedures used for both were relatively simplistic, focusing on level of service targets and not explicitly or implicitly taking into account user heterogeneity.

In fact, user heterogeneity in terms of VOT has long been a fascinating issue in road pricing studies. Edelson (1971) analyzed and compared the socially optimal and monopolistic toll levels in a two-mode network. He showed that in his model framework, the monopolistic toll level is identical with the socially optimal level when the commuters have a homogeneous VOT, but may be lower or higher than the social optimum if their VOTs vary. Mayet and Hansen (2000) investigated the second-best congestion pricing with continuously distributed VOT for a highway with an unpriced substitute. They studied different optimal tolls depending on whether the social welfare function is measured in money or time units (termed respectively as cost-based and time-based social optimum), and whether toll revenue is or is not included as part of the benefit. Small and Yan (2001) investigated the effects of the degree of user heterogeneity on the efficiency of a toll policy by enlarging the VOT difference of two user classes while holding the average VOT constant. Their results suggested that ignoring user heterogeneity may lead to serious underestimation of the efficiency of a value pricing policy. Verhoef and Small (2004) examined the extent to which user heterogeneity affects pricing policy by varying the VOT distribution in various numerical examples. They claimed that the VOT distribution should be considered as "imperfect information" when developing a road pricing policy. Guo and Yang (2009b) incorporated user heterogeneity explicitly and highlighted the discrepancy between the time-based and the cost-based social optimum. Liu et al. (2009) and Nie and Liu (2010) examined Pareto-improving toll schemes in a two-mode network, which makes every users better off compared with the untolled case and examined the impacts of VOT distribution. Guo and Yang (2010) explored Pareto-improving road pricing and revenue refunding schemes in general networks with discrete user classes.

In the context of simultaneous choice of toll level and road capacity, Yang et al. (2002) examined the impact of user heterogeneity on the profitability and social welfare gains from a new toll road in a general network. Xiao and Yang (2008) examined the likely bias of a monopoly market away from the social optimum if each traveler has a unique VOT when a new toll road is introduced parallel to an existing free road connecting a given origin and destination. They investigated the efficiency loss and the road capacity and toll set by a monopolist under different regulatory regimes. Light (2009) investigated the optimal toll and capacity decisions assuming a continuous VOT distribution in the case of congestion or value pricing that involves dividing a highway into free and priced lanes so that at equilibrium the highway effectively operates at two levels of service (the express and high occupancy lanes). He showed that it is beneficial in terms of aggregate social cost to provide such differentiated service.

This study sets out to develop a tractable analytical framework to study the bi-objective BOT problem which simultaneously maximizes social welfare and private profit while allowing for VOT heterogeneity among the users. Extending previous studies, a failure rate and a mean residual VOT function are introduced to characterize user heterogeneity explicitly. The bi-objective maximization problem yields Pareto-efficient BOT contracts that are captured by the three essential decision variables of concession period, toll and capacity. Explicitly incorporating user heterogeneity allows exploration of how the highway's service quality varies along the Pareto-optimal frontier of the two objective functions. Service quality measured in terms of the volume-to-capacity ratio is found to depend on the curvature of the mean residual VOT function: if the VOT distribution has a convex (affine, concave) mean residual VOT function, then the service quality is increasing (identical, decreasing) along the Pareto-efficient frontier from the monopoly optimum to the social optimum. Finally, the outcomes of various regulatory regimes such as a price cap, rate-of-return, or demand and markup-charge regulation are examined in the presence of user heterogeneity. Unlike the case with homogeneous users, none of the regulatory regimes is found to be efficient in achieving a predetermined Pareto-efficient BOT contract.

The paper is organized as follows. The two concepts of failure rate and mean residual VOT functions are introduced to model the BOT problem with heterogeneous users in Section 2; Properties of the set of Pareto-efficient contracts are examined in Section 3. Section 4 examines the behavior of the profit-maximizing private firm under a variety of regulations, and finally, Section 5 concludes the paper.

2. The BOT problem

Suppose that a new BOT toll road is to be built in parallel to an existing free alternative road (or set of roads). The alternative road is assumed to have sufficient capacity without traffic congestion, and its travel time is given by a constant t_A. The BOT toll road is assumed to have a free flow travel time lower than t_A (otherwise it may not attract any users). Let q and y be the travel demand and capacity of the BOT toll road. Denote $t(q,y)$ as the corresponding travel time of the toll road, which is assumed to be a continuously differentiable function of (q,y) for $q \geqslant 0$ and $y > 0$. It is further assumed that, for any $q > 0$, $t(q,y)$ decreases with y, and for any $y > 0$, $t(q,y)$ is a strictly convex and increasing function of q, and $t(q,y) \to +\infty$ with $q \to +\infty$.

Suppose that the VOT among the fixed population Q of road users follows a continuous and differentiable cumulative distribution $F(\beta)$, with a density function $f(\beta)$ and a support $\Theta = (\beta_0, \beta^0) \subset (0, +\infty)$. Verhoef and Small (2004) showed that determining the road capacity y and toll charge level p induces two types of equilibrium: pooling equilibrium and separating equilibrium. The former refers to the corner solution in which all users choose either the free alternative or the toll road.