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Step-tolling with price-sensitive demand: Why more steps in the toll make the consumer better off

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A B S T R A C T

Most dynamic models of congestion pricing use fully time-variant tolls. However, in practice, tolls are uniform over the day, or at most have just a few steps. Such uniform and step tolls have received surprisingly little attention from the literature. Moreover, most models that do study them assume that demand is insensitive to the price. This seems an empirically questionable assumption that, as this paper finds, strongly affects the implications of step tolling for the consumer. In the bottleneck model, first-best tolling has no effect on the generalised price, and thus consumer surplus remains the same as without tolling. Conversely, under price-sensitive demand, step tolling increases the price, making the consumer worse off. The more steps the toll has, the closer it approximates the first-best toll, thereby increasing the welfare gain and making consumers better off. This indicates the importance for real-world tolls to have as many steps as possible: this not only raises welfare, but may also increase the political acceptability of the scheme by making consumers better off.

1. Introduction

Theoretical models of dynamic congestion pricing generally use a fully time-variant toll. However, in practice, there are no such tolls. In practice, tolls are constant over the day, or at most have just a few steps in them. For example, the Oslo toll ring has a uniform toll that is constant over the day (Odeck and Bråthen, 1997), and the London scheme has a uniform toll that is constant between 7:00 and 18:00.[1] In contrast, Singapore uses step tolls: the toll is at its lowest level in the early morning, and increases in steps up to its highest level in the middle of the morning peak; thereafter, it decreases again in steps (see Fig. 1 in Section 2 for an example of a step toll). For the evening peak a similar pattern holds, but this paper will ignore the evening peak. At the "Bugis-Marina Centre (Nicoll Highway)" in Singapore there are seven steps in the toll during the weekday morning peak.[2] The Stockholm pricing scheme has five steps in the morning.[3] But step tolls are also used in the USA: for example, on the SR91 and San Francisco-Oakland Bay Bridge in California, and the SR520 and SR16 Tacoma Narrows bridges in Washington State.[4] Such uniform and step tolls have received surprisingly little attention in the literature. Moreover, models

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[1] This follows www.tfl.gov.uk/tfl/roadusers/congestioncharge/whereandwhen/ as retrieved on 13 June 2012.

[2] Rates for 2 June to 2012 to 5 August 2012, as retrieved on 13 June 2012 from www.onemotoring.com.sg/publish/onemotoring/en/on_the_roads/ERP_Rates.html.

[3] http://en.wikipedia.org/wiki/Stockholm_congestion_tax as retrieved on 13 June 2012.

[4] Respectively www.octa.net/91_schedules.aspx, bata.mtc.ca.gov/tolls/schedule.htm, and www.wsdot.wa.gov/Tolling/TollRates.htm as retrieved on 13 June 2012.

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of step tolls generally assume that demand is fixed and thus insensitive to price.[5,6] This seems an implausible assumption, as empirical research shows that transport demand varies with the generalised price (or price for brevity). For a review of price elasticities, see, for example, Brons et al. (2002) and Graham and Glaiser (2004).

In the bottleneck model, first-best pricing changes the departure rate of drivers (i.e. it changes behaviour), thereby halving marginal social cost and generalised user cost (hereafter referred to as user-cost) for a given number of users. For the social optimum, marginal social cost should equal demand. Due to the halving of marginal social cost, this occurs when the number of users in the first-best equilibrium is the same as in the no-toll equilibrium. Consequently, the price and consumer surplus are unchanged by the tolling. A uniform toll is constant throughout the peak, and causes no change in the departure rate in the bottleneck model. It can only limit congestion cost by reducing demand. The optimal uniform toll equals the marginal external cost (i.e. marginal social cost minus user-cost) when the queue is not eliminated (Arnott et al., 1993). Uniform tolling hence raises the price, and lowers the number of users and consumer surplus. Accordingly, this scheme is comparable to tolling in the textbook static-congestion model, where tolling lowers consumer surplus, and has a substantially lower gain than the first-best bottleneck toll.

Step tolling is in between uniform and first-best tolling: it somewhat changes the departure pattern, but also raises the price. This makes it important to control for price sensitivity of demand when considering step tolling. As this paper finds, in the bottleneck model, the more steps there are, the lower the marginal social cost and price, and the higher consumer surplus. As the number of steps goes to infinity, the step toll generally approaches the first-best toll, and consumer surplus approaches that without tolling.

It may not optimal, or even possible, to use an infinite number of, or very many, steps: in practice, this might be too costly to implement or too difficult for the users to understand. Moreover, users might be insensitive to the very small changes in toll that occur with so many steps. However, experience of, for example, the schemes on the SR91 in California and in Singapore show that users can handle a large number of steps, and in the bottleneck model such schemes already approach the first-best toll very closely. Hence, the practical policy advice from this paper is that it seems better to give a system a substantial number of steps (as is the case in Singapore or on the SR91) than to have a uniform toll or only a few steps (e.g. London and at the Bay Bridge): more steps not only typically raises welfare, but may also increase the acceptability of congestion pricing by making it less harmful for the consumer.

This paper investigates step tolling in three different models that use bottleneck congestion: first, the ADL model following Arnott et al. (1990, 1993); second, the Laih model of Laih (1994, 2004); and, third, the Braking model of Lindsey et al. (2012). In the Laih model, an m-step toll lowers total cost by a fraction $1/2 \cdot m/(1 + m)$. Consequently, with a single step, total cost is reduced by a quarter (or half the gain of the first-best toll); with two steps, the reduction is a third; and, as the number of step goes to infinity, the toll approaches the first-best toll (Laih, 2004). See also Fosgerau (2011) on the Laih toll under general scheduling preferences. In the ADL model, the gain is larger for a finite number of steps, while the toll also approaches the first-best toll as m goes to infinity. The Braking model takes into account that drivers have an incentive to wait to pass the tolling point until just after the toll is lowered: this lowers the toll they pay while only marginally increasing travel time and schedule delay. A consequence of this is that the bottleneck capacity will go unused for some time during the peak, and this inefficiency raises total cost. The inefficiency only increases with the number of steps, and thus the Braking toll never approaches the first-best toll, and always has a lower gain. Furthermore, the other two models are only stable if the government can prevent the braking (Lindsey et al., 2012).[7]

The paper is structured as follows. Next, Section 2 presents a general model of step tolling for any model of dynamic congestion. Then, Section 3 turns to the bottleneck model, and discusses the equilibria without tolling, with first-best tolling, and with step tolling. Section 4 provides a numerical example, and Section 5 carries out sensitivity analyses. Section 6 discusses some limitations of the research and makes suggestions for future research. Finally, Section 7 concludes.

2. The general step-toll model

This section derives the optimal level of the *time-invariant* part of the step toll for a congestion model and a certain form of the step part. The solution assumes that there is a formula for the time-variant part, and is based on the results of Arnott et al. (1993) on a uniform toll and a single-step toll. Table 1 explain the symbols used in this paper.

The toll τ for an arrival time t consists of the time-invariant part θ and a time-variant step part ρ^i (where the level of the step part depends on t and i indicates the ith toll level):

$$\tau[t] = \rho_i + \theta. \tag{1}$$

[5] Interesting exceptions are Arnott et al. (1993), Chu (1999), De Palma et al. (2005) and Ge and Stewart (2010a). Here, the latter three have fixed overall demand. Nevertheless, Chu (1999) has a logit distribution of users over driving alone, carpool and bus; De Palma et al. (2005) have a logit choice of car and public transport; and in Ge and Stewart (2010a,b) only two of the three routes are tolled, making the number of tolled users dependent on the tolls.

[6] Still, although demand is not fixed, it is often rather inelastic. This is especially true when only a single link is priced and there is an unpriced alternative (as is the case with the HOT express-lanes in the USA) or when a single road is widened, since then it also attracts users from alternative routes and modes.

[7] This braking behaviour has been observed in Singapore (Png et al., 1994; Chew, 2008), at the San Francisco-Oakland Bay Bridge (Lee and Frick, 2011), and in Stockholm (Fosgerau, 2011).