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A note on the distortionary effects of revenue-neutral tolls in a bottleneck congestion game

Nicholas Janusch

Department of Economics, St. Lawrence University, 23 Romoda Drive, Canton, NY 13617, United States

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ABSTRACT

This note demonstrates how the redistribution of revenue from a Pigouvian policy can distort incentives and handicap the social objectives of the policy by creating a moral hazard problem. Based on the Levinson (2005) game theory model, I develop a three-player bottleneck congestion game that emulates a repeated prisoner's dilemma and derive efficient tolls. This conceptual game demonstrates the distortionary effects from a revenue-neutral toll policy with lump-sum revenue redistribution and the equity-efficiency tradeoff.

1. Introduction

Marginal cost pricing has been advocated as a way to mitigate the many external costs generated from traffic congestion. These external costs include air, noise pollution, accident costs and road damage externalities in addition to time- and schedule-delay externalities. A congestion toll or tax should account for the time- and schedule-delay externalities which can vary according to place and time of day. However, the fact that motorists are both a willing "victim" as well as a "beneficiary" of the use of roads has policy implications (Hau, 1992). Baumol and Oates (1988) show that so long as the number of victims is large, victims should not be compensated. They argue that the compensation of victims would create a moral hazard problem by incentivizing victims to accept the negative effects of the damages imposed on them resulting in a misallocation of resources with no offsetting benefits to anyone.

But for a Pigouvian policy to be acceptable, the revenue must be redistributed back in some form. Under conditions of "normal" traffic, Hau (1992) shows that if the revenue from an efficient toll policy is kept aside then there will be an efficient allocation of resources; however, the aggregation of "winners" and "losers" of the policy will make society worse off. Therefore, unless the revenues are redistributed back in some form (e.g., reduced user charges, taxes, improved public services,

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E-mail address: nick.janusch@gmail.com

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etc.) neither the users that would still use the tolled road nor the users tolled off the road will endorse the Pigouvian policy. To overcome this hurdle for acceptability, the toll revenue must be redistributed back to society.[1]

Based on Levinson (2005), I show the distortionary effects of a revenue-neutral toll in a "small" group environment using a two-player and a three-player bottleneck congestion game that is further developed in this note. According to the classifications used by Hollander and Prashker (2006) in their review of Non-Cooperative Game Theory games in the transport literature, these type of small-scale discrete games would be classified as concept games as opposed to instrumentals games, since these games focus on small-scale cases of greater problems to establish theoretical principles. The alternative classification, instrument games, are application-orientated games that use full-size cases of realistic scenarios.[2] Therefore, the insights from this conceptual examination highlight the moral hazard problem with lump-sum redistribution, and provides an interesting theoretical demonstration of the tradeoff between efficiency and equity concerns when constructing effective and acceptable Pigouvian policies.

2. Three-player bottleneck congestion game

The congestion problem (i.e., time-delay externalities) can be illustrated by simply reducing and discretizing the problem to just two individuals (Levinson, 2005).[3] The bottleneck congestion game emulates a repeated prisoner's dilemma and can be extended to N discrete players, but each additional player makes the model exponentially more complex and less tractable. The addition of a third player, however, generates a moral hazard problem when revenue-neutral tolls are imposed and the revenue is redistributed lump-sum.

Based on a bottleneck congestion model by Vickrey (1969) and Arnott et al. (1990) where vehicles travel on a single link from a common origin and destination, the Levinson (2005) model assumes homogeneous players simultaneously deciding when to depart in the presence of a bottleneck.[4] Zou and Levinson (2006) extend Levinson (2005) by developing a generalized N-player game and comparing the model's simulated results to the basic bottleneck model. Xin and Levinson (2015) employ a similar stochastic congestion model and simulate different pricing schemes and various compositions of users' aversions of being late.

Each of the three players simultaneously makes their departure decisions based on what they believe will be the other players' departure decisions (Levinson, 2005). The model requires three variables: schedule delay penalties for early arrival (E) and late arrival (L), and the penalty for incurring a journey delay (D). Schedule delay is the deviation from the desired arrival time, and journey delay is the time spent in a queue–the difference between a player's departure time and their actual arrival time. When there are three players, each player has the option of departing: Very Early (v), Early (e), On-time (o), or Late (l). The bottleneck allows for players to arrive only one at a time.

Each of the three players then can arrive in one of six arrival time slots: Very Early, Early, On-time, Late, Really Late (r), and Super Late (s).[5] Congestion occurs if two or more players depart at the same time.[6] The bottleneck randomly determines the allocation of players if congestion occurs. For example in a three-player game, if two players depart at the same time then one player will randomly be sorted to arrive at the intended departure time while the other player will arrive at the next time slot and incur a journey delay. Similarly, if all three players depart at the same time, then one of the three will randomly be determined to arrive at the intended time, another player will be bumped to the next time slot and incur a journey delay, while the third player will be bumped two time slots and incur two journey delays. Each player has the same probability of incurring zero, one, or two journey delays. If a player departs at a time slot immediately after two players depart at the same time, then that player enters a standing queue. Of the two congested players, one will arrive at their intended time while the other player will be journey delayed and arrive at the next time slot which is the departure time of the player that entered a queue. Since it is first come, first serve, the player that arrives in the back of the queue is journey delayed and arrives at the next time slot. In such a scenario where a player enters an existing queue by departing at the time slot immediately after two players create congestion, two of the three players each incur one journey delay.

Using the framework presented by Levinson (2005), Table 2 shows the formalized normal-form game in the perspective of a single player for a three-player bottleneck congestion game with homogeneous players (assuming tolls, represented in the table as τs with unique subscripts, are equal to zero).[7] A more formal mathematical presentation of the game-theoretic model is provided in the Appendix. Each cell represents the ex-ante total expected travel cost (the sum of expected journey- and schedule- delay costs). Some of the cells contain a τ with a unique subscript which represents congestible scenarios for when a toll can be imposed. A τ's subscript represents the toll's efficient magnitude; efficient tolls are derived and discussed

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[1] See Levinson (2010) for a review of equity issues and how they can be addressed.

[2] The second way Hollander and Prashker (2006) classify games is by who the players are. They have classified this category into four groups: games against a demon; games between travelers; games between authorities; and games between travelers and authorities.

[3] The game does not include the other external costs attributed to congestion: operating and maintenance costs, vehicle capital, accidents, government services, and environmental externalities. The congestion literature reports evidence that time-delay and schedule-delay cost externalities are the highest-ranked costs from congestion compared to the other external costs attributed to congestion (Small and Verhoef, 2007; Anas and Lindsey, 2011).

[4] See Levinson and Janusch (2015) for corrigendum to Levinson (2005).

[5] For a two-player game described in Levinson (2005), each decides to either depart: Early, On-time, or Late with the possible arrivals of Early, On-time, Late, and Very Late.

[6] Note that free-flow travel time is normalized to zero (i.e., no journey delays are incurred when there is no congestion).

[7] See Table 1 for nomenclature.