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Abstract

Consider a consumer who can choose to travel on a congestible fast mode or on a congestible slow mode. Users who most value time will use the fast mode A toll on the slow mode can induce some people who initially use that mode to switch to the fast mode A toll on the slow mode with revenue not returned to users then necessarily reduces the welfare of all users A toll on the fast mode may raise aggregate consumer surplus.

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Introduction

A substantial and extensive literature demonstrates that congestion tolls can increase aggregate welfare. Nevertheless, congestion tolls are rarely observed, with Singapore the notable exception Although road tolls are imposed to raise revenue (as on bridges, tunnels, and some highways), almost always the tolls are imposed on the faster of several alternative modes. Thus, highways designed for fast travel may be tolled, but local roads on the same route are not tolled. Governments often charge fees at airports (the fast mode) but not tolls on a road connecting the same cities.

An important observation, well covered by Evans (1992), is relevant. when revenue from a congestion toll is not returned to users of the road, the welfare of road users may decline. In particular. if all consumers suffer identically from a delay, then a toll that is not returned to consumers necessarily reduces the welfare of all consumers (see Weitzman, 1974). If, however, consumers differ in their values of time, then even if the revenue is not returned to users, a congestion toll can raise aggregate consumer welfare (Layard, 1977; Glazer, 1981; Niskanen, 1987; Small, 1992). Evans (1992) shows that the increased consumer welfare is especially likely to appear if the value of time is positively correlated with the value of trips.

Hills (1993) notes, however, that Evans's analysis includes some particular assumptions, leaving open the question of how robust are the results. One assumption is that people cannot switch from one route or mode to another, or in other words that reassignment is absent.

Our paper explicitly considers reassignment, extending earlier studies by considering two congestible modes. The consideration of two modes introduces novel considerations: a toll on a slow mode, rather than inducing some people to stop travelling, may instead cause some to shift to the other mode; and a toll on the fast mode may cause users to switch to the slow mode, inducing some former users of the slow mode to travel less. As we shall see, these effects can cause a toll on the fast mode to be more politically attractive than a toll on the slow mode.

Assumptions

The cost of a trip consists of a congestion cost and of a fixed cost. The congestion cost for each user increases with the number of users on that mode. A user's fixed cost arises even with no congestion, and does not vary with congestion or with the number of other users on the road. The fixed cost can include the costs of fuel or time in free-flowing traffic, disutility from a non-scenic route, the amount of a road toll, and so on. The fixed cost of mode j is called r_j.

The two different modes connect a fixed origin to a fixed destination. Potential users have the same fixed costs for a trip, but may value the trip differently for a given travel time Consumers are indexed by their decreasing willingness to pay for a trip. The number of potential users is sufficiently large that aggregate demand for trips can be described by a twice continuously differentiable function defined over a continuum of consumers. i. Consumers i's willingness to pay for a trip that has travel time T is $p = p(i,T)$. The indexes i are chosen so that $\partial p(i,T)/\partial i \leq 0$: a low value of i indicates a consumer willing to pay a lot for a trip.

The correlation between the valuations of time and trips can in principle have any sign. But we shall follow the literature in assuming that the correlation is either zero or positive. When all consumers value time identically $\partial^2 p/(\partial T \partial i) \equiv p_{Ti}(i,T) = 0$. If $p_{Ti}(i,T) > 0$, then for any given travel time a consumer more highly values time the more highly he values travel.

The trip in question can be made on either of two alternative modes, a slow mode (s) and a fast mode (f). Both modes are congestible. Travel time on mode j, T_j, increases with the number of users, x_j, on that mode. $T_j \equiv T_j(x_j)$, with $\partial T_j/\partial x_j \geq 0$, for $j = s, f$. The modes are physically different. We can think, for example, of a limited access highway and of a local road with traffic lights For any given number of users, the slow mode is slower than the fast mode, in other words, for any value of x, $T_s(x) > T_f(x)$.

Long-run Equilibrium

Our interest is in the effect of a toll on either mode on consumer welfare when the revenue from the toll is not returned to users. Such a measure is likely to give a good indication of which tolls will be politically acceptable — the greater the reduction in consumer welfare, the greater the opposition to a toll. We shall first consider a long-run equilibrium, in which the aggregate number of users varies with the tolls.

Both modes are used in equilibrium only if the fixed cost on the slow mode (mode s) is lower than the fixed cost on the fast mode (mode f), or if $r_s < r_f$. We henceforth assume that this inequality holds. The slow mode is used by the consumers with the lowest value of time. Recall that a high index corresponds to a person who little values time So the people who use the slow mode will have indexes of x_f to $x_s + x_f$. There is no guarantee, however, that all people with indexes in this interval will use the road: for some people, the time costs may outweigh the value of a trip, and so they will not travel. Analogously, some people with high time values may not use the road at all. We henceforth ignore such complications, supposing that all persons with indexes x_f to $x_s + x_f$ use the slow mode, and all persons with indexes 0 to x_f use the fast mode.

The analysis is simplest when all consumers identically value time, $p_{Ti} = 0$ in the relevant range of T. Then in equilibrium the volume of traffic on each mode induces a level of congestion that makes the value of a trip on a mode equal to the fixed cost incurred by each user of that mode:

$$p(x_s + x_f, T_s(x_s)) = r_s, \tag{1}$$

$$p(x_s + x_f, T_f(x_f)) = r_f. \tag{2}$$

In this equilibrium, all consumers value the time difference $T_s - T_f$ identically, and are thus indifferent between the two modes.

The more interesting effects appear when consumers differ in their time valuations. We follow the literature in supposing that people who highly value the trip also highly value time, that is $p_{Ti} > 0$.[1] In equilibrium the value of $T_s - T_f$ (the difference in travel times) unambiguously depends on $r_s - r_f$ (the difference in fixed costs). Thus $p(i,T_s) < p(i,T_f)$ for any individual only if $r_s < r_f$.

Two conditions determine the equilibrium number of users on each mode: (a) the marginal consumer on the slow mode (necessarily a consumer who little values the trip, and hence by assumption who little values time) enjoys no consumer surplus from using the slow mode; (b) the user on the fast mode who least values time is indifferent between using the fast mode and the slow mode.

Analytically, the two conditions mean.

$$p(x_s + x_f, T_s(x_s)) = r_s, \tag{3}$$

$$p(x_f, T_f(x_f)) - p(x_f, T_s(x_s)) = r_f - r_s. \tag{4}$$

Below we shall give some numerical solutions to these equations.

Consumer Welfare

Aggregate consumer surplus (when equations (3-4) describe behaviour) is

$$S = \int_0^{x_f} p(i, T_f(x_f))di + \int_{x_f}^{x_s + x_f} p(i, T_s(x_s))di - r_s x_s - r_f x_f. \tag{5}$$

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1 See, for example, Layard (1977) and Lave (1994).

Consider first the effects of a toll on the fast mode, f. The toll induces those users of f who least value trips and time to switch to the slow mode, s. The increased congestion on s causes users on s who least value trips and time to leave. The toll on the fast mode unambiguously hurts consumers who initially used the slow mode.

What about people who initially used the fast mode? The toll unambiguously hurts initial users of the fast mode who least value travel and time. The welfare of people who most value time can either rise or fall; they pay the higher tolls. but enjoy lower congestion. If their welfare rises by more than the welfare of others falls, then the toll can raise aggregate consumer welfare.

Second, consider the effects of a toll on the slow mode.[2] The toll makes initial users of the slow mode who least value travel and time stop travelling. The toll thus reduces the welfare of the consumers who become non-users. Initial users of the slow mode who most value travel and time can either gain or lose Users who lose switch to the fast mode. The switch to the fast mode increases congestion on that mode; consumers on both sides thus lose. If instead some users of the slow mode gain, then some users of the fast mode (those users who least value time) will switch to the slow mode. Thus, when a toll on the slow mode induces people to switch to the slow mode, aggregate consumer surplus can rise. This effect will be especially strong when many consumers place both a low value on the trip and a low value on time. Even a small toll on the slow mode therefore greatly reduces use of the slow mode, increasing welfare of users in the slow mode. If some initial users of the fast mode switch to the slow mode. and some users on the fast mode highly value the reduced travel time, then welfare of users on the fast mode can increase as well.

The different effects of tolls on demand generate simple rules for determining the welfare effects of tolls when the revenue is not returned to users. A toll on the slow mode or a toll on the fast mode can increase aggregate consumer welfare only if use of the fast mode declines. A toll on the fast mode necessarily reduces the welfare of users on the slow mode; a toll on the slow mode can, but need not, increase aggregate welfare of users on both modes.

We illustrate some of these effects with an example. Let travel time on mode j have the linear form $T_j = \alpha_j + x_j$. Let consumers i's willingness to pay for a trip that has travel time T be $F - i - (G - i)T$.

For these functional forms equations (3) and (4) become

$$F - (x_s + x_f) - (G - x_s)(\alpha_s + x_s) = r_s, \tag{6}$$

and

$$F - x_f - (G - x_f)(\alpha_f + x_f) - [F - x_f - (G - x_s)(\alpha_s + x_s)] = r_f - r_s. \tag{7}$$

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[2] We assume that the toll is sufficiently small that s continues to be the slow mode

Aggregate consumer surplus on the slow mode is

$$CS_{slow} = \int_{x_f}^{x_s + x_f} [F - i - (G - i)T_s]di - r_s x_s$$

$$= Fx_s - \frac{1}{2}x_s^2 - x_s x_f - T_s G x_s + \frac{1}{2}T_s x_s^2 + T_s x_s x_f - r_s x_s \quad . \qquad (8)$$

Aggregate consumer surplus on the fast mode is

$$CS_{fast} = \int_0^{x_f} [F - i - (G - i)T_f]di - r_f x_f$$

$$= Fx_f - \frac{1}{2}x_f^2 - T_f G x_f + \frac{1}{2}T_f x_f^2 - r_f x_f \quad . \qquad (9)$$

We cannot solve these equations analytically, so we give some numerical solutions. Let $F = 20$, $G = 15$, $\alpha_f = 0$, $\alpha_s = 0.3$, $r_s = 0$; we vary r_f as shown below. We see in Table 1 that as the toll on the fast mode increases, aggregate consumer surplus for users of the fast mode increases (from 1.004 to 1.022). Consumer welfare on the slow mode declines.

Table 1

Effect of Toll on Fast Mode

r_f	x_s	x_f	T_s	T_f	CS_{slow}	CS_{fast}	CS^0_{fast}	CS^{xf}_{fast}
0.1	0.965	1.287	1.265	1.287	1.447	1.004	0.595	0.965
0.2	0.965	1.280	1.265	1.279	1.439	1.006	0.608	0.965
0.3	0.966	1.272	1.266	1.272	1.431	1.008	0.620	0.966
0.4	0.966	1.265	1.266	1.265	1.423	1.010	0.632	0.966
0.5	0.967	1.257	1.267	1.257	1.415	1.012	0.644	0.967
0.6	0.967	1.250	1.267	1.250	1.407	1.014	0.655	0.967
0.7	0.968	1.242	1.268	1.242	1.399	1.015	0.667	0.968
0.8	0.968	1.235	1.268	1.235	1.391	1.017	0.679	0.968
0.9	0.969	1.227	1.269	1.227	1.383	1.018	0.690	0.969
1.0	0.969	1.220	1.269	1.220	1.375	1.019	0.701	0.969
1.1	0.970	1.213	1.270	1.213	1.367	1.020	0.712	0.970
1.2	0.970	1.205	1.271	1.205	1.359	1.021	0.723	0.970
1.3	0.971	1.198	1.271	1.198	1.350	1.021	0.734	0.971
1.4	0.972	1.190	1.272	1.190	1.342	1.022	0.745	0.972
1.5	0.972	1.183	1.272	1.183	1.334	1.022	0.756	0.972

For a more refined view consider the welfare of the consumer who most highly values travel. This is the consumer with index 0, and we show his consumer surplus by CS^{0}_{fast}. The user of the fast mode who is just indifferent between using that mode and using the slow mode has index x_f. The Table lists consumer surplus in the column headed CS^{xf}_{fast}, and shows that consumer surplus increases with the toll on the fast mode.[3] And since people with lower indexes value time savings more highly, if a consumer with index x_f benefits from the toll, then so do all consumers with lower indexes.

Table 2 gives some numerical results when the toll on the slow mode is varied. As before, we set $F = 20$, $G = 15$, $\alpha_f = 0$, and $\alpha_s = 0.3$. Let $r_f = 0.5$.

Table 2
Effect of Toll on Slow Mode

r_s	x_s	x_f	T_s	T_f	CS_{slow}	CS_{fast}	CS^{0}_{fast}	CS^{xf}_{fast}
0 1	0 965	1.184	1 265	1 183	1 321	1 013	0 748	0 965
0 2	0 957	1 184	1.258	1 184	1 308	1 005	0 740	0.957
0 3	0 950	1.185	1 250	1 185	1 294	0 996	0.732	0 950
0.4	0 943	1 185	1 243	1 185	1 281	0 987	0 724	0 943
0 5	0 936	1 186	1 236	1 186	1 268	0 979	0 716	0 936
0.6	0 928	1 186	1 228	1 186	1.254	0 970	0 708	0 928
0 7	0.921	1 187	1 221	1 187	1 241	0.962	0 700	0.921
0 8	0.914	1 187	1 214	1 187	1 228	0 953	0 692	0.914
0.9	0 907	1 188	1.207	1 188	1 215	0 944	0 684	0.907
1 0	0 899	1 188	1 199	1 188	1 201	0 936	0 676	0 899
1 1	0 892	1 189	1 192	1 189	1 188	0 927	0 668	0 892
1 2	0.885	1 189	1 185	1 189	1.175	0 919	0.660	0.885
1.3	0 878	1 190	1 178	1 190	1 162	0 910	0 652	0.878
1 4	0 871	1 190	1.171	1 190	1.148	0 901	0 644	0.871

For the parameters in this table, an increase in r_s, the toll on the slow mode, reduces aggregate consumer welfare on both modes. This decline also appears for all the many other parameter values we checked. Of course, the result is not perfectly general. For example, if many consumers little value a trip and time, then when $r_s = 0$ congestion will be high and consumer surplus low. An increase in the toll can therefore increase consumer welfare. Nevertheless, it appears that under plausible conditions a toll on the fast mode will increase welfare, whereas a toll on the slow mode will not. This is explored further in the next section.

[3] Of course, some initial users may suffer from the toll and switch to the slow mode

Short-run Equilibrium

In political evaluations of tolls the short-run effects on welfare are likely to be the most important. For example, if people vote retrospectively and if the term of office for the incumbent is short, then political support for a toll depends largely on its immediate effect. Similarly, in a community with large population movements, current voters will care about short-term welfare, rather than with the long-term effects of tolls. For these reasons, it is important to consider the short-run effects of tolls We continue to evaluate consumer welfare under the assumption that toll revenues are not returned to users For our short-run analysis we let the sum of users of the two modes be fixed.

Consumer Welfare

Consider a toll on the fast mode Some initial users of the fast mode (those users on it who least value time) will switch to the slow mode. This switch increases congestion on the slow mode, and unambiguously hurts all users of the slow mode.[4] The remaining users of the fast mode suffer less congestion. If the remaining users value time sufficiently, then users of the fast mode can gain. Thus, a toll on the fast mode can raise aggregate consumer welfare.

Consider next a toll on the slow mode. The toll will induce some people (the ones initially on the slow mode who most value time) to switch to the fast mode. The switch to f increases congestion on that mode The welfare of all users on f therefore declines. And by the principle of revealed preference, the people who switch from the slow mode to the fast mode necessarily lose. By assumption people remaining on s value time less than people switching to the fast mode. So all consumers on the slow mode also lose. Thus, in the short run a toll on the slow mode hurts all users

The short-run harm to users from a toll on the slow mode but not on the fast mode is consistent with a political explanation that supposes that users are politically powerful. Thus, turnpikes (which are presumably faster than alternative modes) are often tolled roads. Highly congested urban roads are not. Indeed, our approach says that, other things being equal, the slower a congested road is compared to a faster mode, the less politically acceptable a congestion toll is on the slow road.[5]

For a formal analysis of the effects of tolls. define the fixed number of users as $X \equiv x_s + x_f$. Omit equation (3), which is now inapplicable, and eliminate x_s from (4) to obtain the equilibrium condition

[4] The loss to users of s, however, may be small if most users of s value time little

[5] In contrast, Knight (1924) assumes the existence of a *fast congested* mode and a *slow uncongested* mode.

$$p(x_f, T_f(x_f)) - p(x_f, T_s(X - x_f)) = r_f - r_s. \quad (10)$$

The equation can be solved for x_f as a function of r_s and r_f. The derivatives of x_f with respect to r_s and r_f are

$$\frac{\partial x_f}{\partial r_s} = -\frac{\partial x_f}{\partial r_f} \quad (11)$$

$$= -\frac{1}{p_i(x_f, T_f) - p_i(x_f, T_s)} + p_T(x_f, T_f)T_{xf} + p_T(x_f, T_s)T_{xs}.$$

Since $p_i(x_f, T_f) - p_i(x_f, T_s) \leq 0$, and $p_T \leq 0$, the expression on the right-hand side is positive.

Aggregate consumer surplus, derived from (5), is

$$S = \int_0^{x_f} p(i, T_f(x_f))di + \int_{x_f}^{x_s + x_f} p(i, T_s(x_s))di - r_s x_s - r_f x_f \quad (12)$$

Differentiate (12) with respect to r_s (the toll on the slow mode) to obtain

$$\frac{\partial S}{\partial r_s} = [p(x_f, T_f) - p(x_f, T_s) - r_f + r_s]\frac{\partial x_f}{\partial r_s} \quad (13)$$

$$+ \left[\int_0^{x_f} p_T(i, T_f)di \frac{\partial T_f}{\partial x_f} - \int_{x_f}^{x_s + x_f} p_T(i, T_s)di \frac{\partial T_s}{\partial x_f}\right]\frac{\partial x_f}{\partial r_s} - x_s.$$

This expression makes use of the obervation that in the short run

$$\frac{\partial x_s}{\partial r_s} = -\frac{\partial x_f}{\partial r_s} \text{ and that } \frac{\partial (x_f + x_s)}{\partial r_s} = 0.$$

From the equilibrium condition $[p(x_f, T_f) - r_f] - [p(x_f, T_s) - r_s] = 0$, and so the first term is zero. Examining the integral terms, note that consumers suffer from increased time on the road, so that $p_T(i, T_f)$ and $p_T(i, T_s)$ are negative. Note further that

$$\frac{\partial T_f}{\partial x_f} > 0, \text{ that } \frac{\partial T_s}{\partial x_f} < 0, \text{ and that } \frac{\partial x_f}{\partial r_s} > 0.$$

Thus the second line in the expression is also negative, and the derivative is negative, meaning that any toll on the slow mode hurts consumers. In summary, if the total number of users is fixed, and if toll revenue is not returned to users, then users always suffer from a toll on the slow mode

We can also show that a toll on both modes cannot maximise consumer welfare. For suppose that both r_s and r_f are positive. Let $d \equiv r_f - r_s$. If $d > 0$, then the same effects on consumer behaviour are attained by leting $r_s = 0$ and $r_f = d$. The lower tolls necessarily aise consumer welfare. A similar argument applies when $d < 0$ Thus, users may gain only from a toll on the fast mode. If toll revenues from the fast mode are used to subsidise users of the slow mode, then a toll on the fast mode is yet more attractive. These results may explain why we often see a toll on the faster mode but not on the slower mode.

Social Welfare

Consider next the effect of tolls on social welfare. Social welfare differs from consumer surplus by considering toll revenue as a transfer payment rather than as a cost. We shall see that, in the short run, maximising social welfare, unlike maximising consumer welfare, can require a toll on the slow mode.

Let the toll on mode i be t_i. Interpret r_s and r_f as the fixed costs of travel other than the tolls; let these also represent all social costs other than congestion. Replace (10) by

$$p(x_f, T_f(x_f)) - p(x_f, T_s(x_s)) = r_f - r_s + t_f - t_s. \tag{14}$$

Social welfare, W, is then given by (12). Set $t_f = 0$ and differentiate with respect to t_s to obtain

$$\frac{\partial W}{\partial t_s} = \left[-t_s + \int_0^{x_f} p_T(i, T_f) T_{xf} di - \int_{x_f}^{x_s + x_f} p_T(i, T_s) T_{xs} di \right] \frac{\partial x_f}{\partial t_s}. \tag{15}$$

The sign of the first factor on the right-hand side is ambiguous. Social efficiency requires a toll on the congested mode, regardless of whether it is the faster or slower mode.

Conclusion

Standard results on congestion tolls show that they are necessary to maximise social welfare, but that when the revenue from the tolls is not returned to users of the road, the welfare of the users can decline. That may largely explain why congestion tolls are so rare. An exception to this result appears when consumers differ in their valuation of time — a congestion toll can then increase the welfare of some road users, and also increase the aggregate welfare of road users.

This paper considered heterogeneous consumers, showing how a congestion toll can increase aggregate consumer welfare. The new element in the paper is that users can choose between different modes. The analysis allowed us to describe the pattern of tolls that do not arouse consumer opposition. In the short run, any toll on the slow mode will reduce consumer welfare. In contrast, a toll on the fast mode may increase aggregate consumer welfare. Lastly, the set of tolls that maximise consumer welfare will not impose a toll on both modes.

Thus, we find that differential tolls are likely to face less political opposition than tolls on all modes. If tolls do benefit consumers then they are likely to be progressive. That is, if we make the reasonable assumption that the value of time increases with the wage rate, then the tolls that maximise consumer welfare will be on the fast mode only, thereby raising revenue only from more affluent consumers. Such a set of tolls, however, will (at least in the short run) increase congestion on the slow mode, which was presumably the most congested one to begin with. An ironic implication is that politically acceptable tolls may increase congestion or increase average travel times.

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