ROAD PRICING, PUBLIC TRANSPORT AND MARKET STRUCTURE

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1. Introduction

Privatization of surface transportation has been a worldwide trend for many years. Many toll roads and public transport systems are now privately operated and much has been written about how well they perform. Several studies consider road pricing and public transit service provision jointly under alternative market arrangements and different assumptions about traffic congestion. Small (2004) analyzes socially optimal bus service when buses and cars share the road and cars can be tolled. Ahn (2009) considers competition between a public toll road and a privately-operated bus service. Wang et al. (2004) study competition between a private toll road and private transit companies when there is no traffic congestion. And Pels and Verhoef (2007) look at road-rail competition when both modes are congestible but use separate rights of way.

To the best of our knowledge, competition between a private toll road and public transit service using the same right of way has not yet been studied. This paper makes a first pass at such an analysis. Section 2 describes the model. Section 3 presents analytical results for tolls and fares in several alternative market regimes that differ in how bus fares are set. Section 4 presents a numerical example and Section 5 concludes.

[1] Financial support from the Social Sciences and Humanities Research Council of Canada is gratefully acknowledged.

2. The Model

The model is adapted from Ahn (2009). Individuals travel on a fixed route either by car (*A*) or by bus (*B*). They differ only in their willingness to pay for a trip so that travel demands can be described using a representative consumer model. Utility of the representative consumer is given by the quasi-linear function $U\left(q^A,q^B\right)+g$ where q^A is the number of car trips, q^B is the number of bus trips, and *g* is a composite numeraire consumption good. Function $U(\cdot)$ is assumed to be strictly quasiconcave; car trips and bus trips are therefore imperfect substitutes. Given income *y*, and full prices (i.e., generalized costs) for car trips and bus trips of p^A and p^B respectively, utility net of any government transfer can be written

(1) $$U\left(q^A,q^B\right)+y-p^Aq^A-p^Bq^B .$$

Given *m* individuals, the total numbers of car trips and bus trips are $Q^A=mq^A$ and $Q^B=mq^B$ respectively. Each car traveler drives alone; the number of cars on the road is thus Q^A. Buses carry *s* passengers and they operate full. The number of buses in service is therefore $n=Q^B/s$.[2] Cars and buses share the road and delay each other. The time cost of a car trip, $C^A\left(Q^A,n\right)$, is assumed to be a differentiable and strictly increasing function of Q^A and *n*. The in-vehicle time cost of a bus trip, $C^B\left(Q^A,n\right)$, has the same properties. Specific assumptions about the functional forms of $C^A(\cdot)$ and $C^B(\cdot)$ are made in Section 4.

The full price of a car trip is

(2) $$p^A=\tau+\overline{c}^A+C^A\left(Q^A,n\right)$$

[2] Ahn (2009) assumes that buses travel with fewer than *s* passengers. Formulas for fares, tolls and bus service frequency all differ when buses operate at capacity.

where τ is the toll (if any) imposed on cars, and $\overline{c}^A$ denotes fuel consumption, parking and any other car-related costs. The full price of a bus trip is

$$p^B = f + w(n) + C^B\left(Q^A, n\right) \tag{3}$$

where f is the fare and $w(n)$ is waiting time plus schedule delay cost. Function $w(n)$ is assumed to be a decreasing function of *n* since larger values of *n* imply shorter time headways between buses.

The long-run cost of bus service (including capital, operation and maintenance) is given by a differentiable and strictly increasing function, $K(n)$. Welfare is measured by social surplus. Given Eq. (1), and $n = Q^B / s$, social surplus can be written

$$W = \underbrace{m\left(U\left(q^A, q^B\right) + y - p^A q^A - p^B q^B\right)}_{[a]} + \underbrace{fQ^B - K\left(Q^B / s\right)}_{[b]} + \underbrace{\tau Q^A}_{[c]} . \tag{4}$$

In Eq. (4), term [a] is consumers' surplus, term [b] is bus system profits and term [c] is toll revenue. [3]

Individuals choose q^A and q^B so that their marginal willingness to pay for trips by each mode matches the respective full prices in Eqs. (2) and (3). If marginal willingness to pay is expressed in terms of inverse demand functions, $P^i\left(q^A, q^B\right)$, $i = A, B$, the equilibrium conditions are $P^i\left(q^A, q^B\right) = p^i$, $i = A, B$. Using these conditions it is straightforward to derive how p^A, p^B, Q^A and Q^B vary with marginal changes in τ and f. These derivatives are used to derive the values chosen for τ and f in each market regime.[4]

[3] Costs of collecting bus fares and tolls are ignored.
[4] Due to space constraints these derivatives as well as all derivations in Section 3 are omitted.

3. Analytical Comparison of Market Structures

Several market regimes with a private toll-road operator and bus service will be studied. To facilitate understanding of how well they function, we begin by deriving the first-best and second-best optima.

First-best optimum

In the first-best optimum prices of car trips and bus trips are chosen to maximize social surplus in Eq. (4). The optimal car toll is:

(5)
$$\tau^O = \underbrace{C_A^A Q^A}_{[a]} + \underbrace{C_A^B Q^B}_{[b]}$$

where superscript *O* denotes the first-best optimum. Term [a] in Eq. (5) is the marginal external congestion cost that a car trip imposes on other car users. Term [b] is the corresponding cost imposed on bus users. The optimal car toll is set equal to the sum of these external costs. It is unnecessary to impose a toll on buses because service is publicly controlled. In Ahn's (2009) model buses run with spare capacity and it is also unnecessary to include a road congestion charge in the fare because an additional passenger can be accommodated without expanding capacity.[5] The traffic congestion that buses create is internalized through choice of bus frequency. The situation differs here since buses run full, and capacity cannot be chosen independently of the fare. The optimal fare works out to be the long-run marginal capital, operating and external cost of running another bus divided by bus capacity:

(6)
$$f^O = \frac{1}{s}\left(\underbrace{C_n^A Q^A}_{[a]} + \underbrace{C_n^B Q^B}_{[b]} + \underbrace{w_n Q^B}_{[c]} + \underbrace{K_n}_{[d]} \right).$$

Terms [a] and [b] are analogous to terms [a] and [b] in Eq. (5) for the first-best toll. Term [c] reflects the effect of an additional passenger on the waiting time cost borne by other passengers. Term [c] is negative because $w(n)$ is a decreasing function of *n*, more buses

[5] Bus passenger boarding and alighting delays, crowding inside buses and at bus stops, and other types of interference between passengers are ignored both in Ahn's model and here.

must be added to accommodate additional passengers, and the higher frequency creates a positive external benefit for existing riders.

Second-best optimum

In the second-best optimum the public operator (henceforth called the "agency") cannot control the price of car trips — either because a toll cannot be levied or because the toll is set at a non-optimal level as is the case in the private-toll-road regimes. The agency sets the fare while taking into account the distorted price of car trips as measured by the deviation between the first-best toll formula in Eq. (5) and the toll actually set: $e^A \equiv C_A^A Q^A + C_A^B Q^B - \tau$. The second-best fare is

$$f^s = \frac{1}{s}\left(\underbrace{C_n^A Q^A}_{[a]} + \underbrace{C_n^B Q^B}_{[b]} + \underbrace{w_n Q^B}_{[c]} + \underbrace{K_n}_{[d]}\right) \underbrace{- e^A \frac{P_B^A}{P_A^A - C_A^A}}_{[e]} \tag{7}$$

where superscript S denotes the second-best optimum. Terms [a] - [d] in Eq. (7) are interpreted as in Eq. (6). In term [e], $C_A^A > 0$ while the derivatives of the inverse demand functions, P_A^A and P_B^A, are both negative. Term [e] is therefore negative if car use is underpriced ($e^A > 0$) and positive if it is overpriced ($e^A < 0$). The second-best fare deviates from the first-best fare in order to alleviate market distortions in car travel. Attention now turns to three market regimes that feature a private toll road and different rules for setting fares.

Private toll road and public bus operator: Regime P

In Regime *P* a private operator (henceforth called the "firm") chooses the toll for cars at the same time as the agency chooses the fare. It might seem natural for the firm to set a toll on buses as well. However, the firm has monopoly power as provider of essential infrastructure (the road) and could set a very high toll that would severely curtail bus ridership.[6] A more efficient arrangement is that,

[6] If firm and agency both impose charges on bus users there is a double marginalization problem that exacerbates overpricing of bus trips. Double marginalization arises in

perhaps as part of the firm's toll concession agreement, the agency pays the firm a lump-sum fee for unlimited access for buses. Such a fee does not affect either the levels chosen for the car toll and fare or the numbers of car and bus trips taken.[7]

Given this arrangement, the firm chooses τ to maximize toll revenue, τQ^A, subject to the downward-sloping demand curve for car trips, $Q^A\left(p^A\right)$, that is implicitly defined by the user equilibrium conditions. The solution is

$$(8) \qquad \tau^P = \underbrace{C_A^A Q^A}_{[a]} \underbrace{- P_A^A Q^A}_{[b]} + \underbrace{\frac{\left(P_A^B - C_A^B\right)\left(P_B^A - C_n^A / s\right)}{P_B^B - \left(w_n + C_n^B\right)/s} Q^A}_{[c]}$$

where superscript *P* denotes the first private-toll-road regime. Term [a] in Eq. (8) matches term [a] in Eq. (5) for the first-best toll, but there is no counterpart for term [b] in Eq. (5) because the firm does not care about bus travel times per se. Term [b] in Eq. (8) is a (standard) price markup proportional to the firm's market power as measured by the slope, P_A^A, of the inverse demand for car trips. Term [c] depends on the slopes of the inverse demand curves for car and bus trips as well as on the slopes of the travel time functions, C^A and C^B. Term [c] is zero if the demand and travel time costs of bus trips are both independent of car volume (i.e., $P_A^B = C_A^B = 0$) since the car toll then has no feedback effect on the number of bus trips taken. Term [c] is also zero if car trip demand and costs are independent of bus volume (i.e., $P_B^A = C_n^A = 0$) since any effect of the car toll on bus trips then has no effect on car toll revenue. If the numbers of car and bus trips are interdependent, term [c] is negative. The firm has an incentive to reduce the toll because doing so shifts people from buses to cars, and reduces the number of buses in operation that delay cars and reduce demand for car trips.

Wang et al. (2004) who consider a market in which one firm operates bus service, and another firm charges the first firm for use of the road.

[7] The fee does not affect social surplus either since toll revenue is a transfer from the public to the private purse and nets out in Eq. (4).

Given the propensity of the firm to exploit market power one might expect the private toll to exceed the first-best toll. However, the ranking is theoretically ambiguous because term [c] in Eq. (8) is negative and Eq. (8) lacks a counterpart to Term [b] in Eq. (5).[8] The ranking therefore hinges on the magnitude of markup [b] in Eq. (8) relative to term [c] in Eq. (8) and term [b] in Eq. (5). Inspection of the two equations suggests that τ^O is likely to exceed τ^P when:

– many bus trips are taken, and buses are susceptible to congestion, so that cars impose high congestion costs on buses (i.e., term [b] in Eq. (5) is large);
– car trip demand is relatively price elastic, so that markup term [b] in Eq. (8) is small;
– buses impose relatively large delays on cars (C_n^A is large), and relatively small delays on other buses (C_n^B is small), so that the negative feedback effect of a higher toll on increased bus trips is large (i.e., term [c] in Eq. (8) is large in magnitude).

The optimal fare is derived by substituting Eq. (8) for the toll into e^A, and the resulting expression for e^A into Eq. (7). (The formula is cumbersome and is omitted to economize on space.) Since e^A can be positive or negative, the second-best fare can be greater or smaller than the first-best fare in Eq. (6).

Private toll road and public bus operator as leader: Regime T

Regime T features a two-stage game. In stage 1 the agency chooses the fare, and in stage 2 the firm sets the toll. The agency therefore acts as a Stackelberg leader. Because the firm moves second, it uses the same decision rule, Eq. (8), to set the toll as in Regime P. The agency chooses a fare taking into account how it affects the toll. The

[8] The firm tolls cars, but not buses. This parallels in some respects the setting considered by Calthrop et al. (2007) in which cars and trucks share the road and only trucks are tolled. The setting here differs in two respects. First, the toll road operator seeks to maximize profit rather than welfare, and second the two modes are imperfect substitutes for the same group of travelers rather than modes used by separate groups (i.e., passengers and freight transporters) with independent demands.

fare does not appear explicitly in Eq. (8), but it can affect all component terms in Eq. (8) except bus capacity, *s*. Although the slope of the firm's response curve, $\tau^P(f)$, is theoretically ambiguous, it is likely to be positive because a higher fare boosts car traffic and hence increases both the firm's market power and congestion delays for cars.

Integrated private operation of toll road and bus service: Regime I

In Regime *I*, a single firm controls both the road and bus service. Bus frequency is again determined by the capacity constraint, $n = Q^B / s$. The joint profit-maximizing toll and fare work out to:

(9) $$\tau^I = \underbrace{C_A^A Q^A}_{[a]} + \underbrace{C_A^B Q^B}_{[b]} \underbrace{-P_A^A Q^A}_{[c]} \underbrace{-P_A^B Q^B}_{[d]},$$

(10) $$f^s = \frac{1}{s}\left(\underbrace{C_n^A Q^A}_{[a]} + \underbrace{C_n^B Q^B}_{[b]} + \underbrace{w_n Q^B}_{[c]} + \underbrace{K_n}_{[d]} \right) \underbrace{-P_B^A Q^A}_{[e]} \underbrace{-P_B^B Q^B}_{[f]}.$$

Terms [a] and [b] in Eq. (9) match the corresponding terms in Eq. (5) for the first-best toll. Terms [c] and [d] are markups that reflect market power. Terms [a] through [d] in Eq. (10) match the corresponding terms in Eq. (6) for the first-best fare, and terms [e] and [f] are markups. The integrated firm incorporates into the toll and fare equations congestion delays, bus waiting time costs, and bus operating costs, but it adds a markup to each price. This suggests that the numbers of car trips and bus trips are both below first-best levels. The numerical example presented in the next section bears this out.

4. A Numerical Example

The analysis in Section 3 provides insights into the various market regimes, but it does not identify either their quantitative differences or their efficiency rankings. To do so, a numerical example is now developed. As in Ahn (2009), demand functions are assumed to be linear for each mode. The underlying utility function is[9]

[9] The notation differs from Ahn's notation.

(11) $U\left(q^A, q^B\right) = a^A q^A + a^B q^B - \left(b^A \left(q^A\right)^2 + b^B \left(q^B\right)^2\right)/2 - dq^A q^B$.

Travel time functions are also linear:

(12) $C^A\left(Q^A, n\right) = c_0^A + c_A^A Q^A + c_n^A n$, $C^B\left(Q^A, n\right) = c_0^B + c_A^B Q^A + c_n^B n$.

Bus users do not know the timetable. They arrive at a bus stop randomly, and wait on average for half the time headway between buses. Waiting time and schedule delay costs are proportional to waiting time. Expected waiting time cost is therefore

(13) $$w(n) = \alpha/(2n) ,$$

where α is the cost per hour of waiting time plus schedule delay. The total cost of bus service is proportional to the number of buses used:

(14) $$K(n) = kn .$$

Base-case parameter values are given in Table 1.[10] Equilibria for the various regimes are summarized in Table 2.

In the first-best optimum, 56% of travelers go by bus. They are accommodated in 109 buses which operate full.[11] Due to the higher assumed free-flow travel time cost of bus trips, travel time costs are higher for bus trips than for car trips. However, the toll greatly exceeds the fare, and the full price of a trip is nearly $3 higher by car than by bus. The relatively large full-price elasticity of car trips is attributable in part to the large fraction of trips made by bus.[12] Congestion delay amounts to a little over a half of free-flow travel time for car trips, and a little over a third for bus trips.

In the second-best optimum, cars cannot be tolled. Although the fare is set below zero, which results in a substantial operating loss, the

[10] The values chosen are broadly descriptive of a 10 km. commuting route that is fairly congested in the second-best optimum. Door-to-door free-flow travel time is higher for bus trips than car trips because of walk access time and the time required for buses to serve bus stops.

[11] Bus capacity is binding in all five market regimes with the base-case parameters as well as all alternative parameter combinations considered in the sensitivity analysis.

[12] According to Santos and Fraser (2006) the price elasticity of car trips in London is high for this reason.

number of car trips is about a third higher than in the first-best optimum and traffic congestion is appreciably worse.

Table 1: Base-case parameter values

m	2,000 travelers	c_A^A, c_A^B	\$5 x 10^{-4}/trip
a^A, a^B	\$36/trip	c_n^A, c_n^B	\$1 x 10^{-3}/trip
b^A, b^B	\$6/trip^2	α	\$25/hr.
d	\$1.80/trip^2	s	60 passengers
$\overline{c}^A$	\$1.30/trip	k	\$75 per bus
c_0^A	\$5/trip	y	immaterial
c_0^B	\$7.83/trip		

In private-toll-road Regime *P*, the toll is nearly twice the first-best toll. Car traffic is now well below its first-best level while bus traffic is slightly above it. To counter overpricing of car trips the fare is set at more than twice the first-best level. Surplus ends up slightly higher than in the second-best outcome. Thus, introduction of tolling by a profit-maximizing firm results in a modest welfare gain. The gain can be compared with the gain from implementing the first-best optimum using the index $r^j \equiv \left(W^j - W^S\right)/\left(W^O - W^S\right)$ where j indexes the regime. For Regime *P*, r^P =0.194.

When the agency is a Stackelberg leader (Regime *T*) it sets a fare \$0.74 lower than in Regime *P* in order to induce the firm to lower the toll. However, the firm drops the toll only by \$0.12, the welfare improvement is very small, and the efficiency index increases only marginally to r^T =0.211. If the firm controls bus service as well as the road (Regime *I*) it exploits its overall markup power by setting a very high toll and fare. The total number of trips falls to slightly less than half the second-best optimal level, and bus service is cut by a similar fraction. Loss of consumers' surplus to travelers outweighs the firm's gain in bus profits and toll revenue, and a substantial welfare loss is incurred with r^I =-4.995.

Table 2: Base-case equilibria

	Benchmark regimes		Private toll road regimes		
	First best	Sec. best	Nash (P)	2-stage (T)	Joint (I)
Q^A	5,131	6,852	3,586	3,549	3,169
Q^B	6,477	6,239	6,692	6,956	3,244
$Q^A + Q^B$	11,608	13,091	10,277	10,505	6,414
n	109.0	104.0	111.5	115.9	54.1
τ	$5.80	—	$11.02	$10.90	$15.63
f	$1.33	-$0.37	$2.85	$2.11	$13.71
C^A	$7.67	$8.53	$6.90	$6.89	$6.64
C^B	$10.51	$11.36	$9.74	$9.72	$9.47
p^A	$14.78	$9.83	$19.22	$19.09	$23.57
p^B	$11.95	$11.12	$12.70	$11.93	$23.41
Full price elasticities					
Car, Car	-1.06	-0.53	-1.96	-1.97	-2.72
Car, Bus	0.26	0.18	0.39	0.37	0.81
Bus, Bus	-0.68	-0.65	-0.70	-0.63	-2.64
Bus, Car	0.25	0.17	0.32	0.30	0.80
Congestion delay as a fraction of free-flow travel times					
Car trips	0.535	0.706	0.381	0.378	0.328
Bus trips	0.341	0.451	0.243	0.241	0.209
Welfare components					
Bus profit	$503	-$10,084	$10,697	$5,963	$40,430
Toll rev.	$29,781	—	$39,501	$38,693	$49,546
Surplus	$162,618	$157,191	$158,242	$158,337	$130,084
Efficiency			0.194	0.211	-4.995

Sensitivity analysis

Equilibria for all five regimes are sensitive to the severity of congestion. Of perhaps greatest interest is the effect of congestion on the performance of Regime *P*. This is examined in Figure 1 by plotting τ^O, τ^P and r^P against a congestion index constructed by varying coefficients c_A^A, c_n^A, c_A^B and c_n^B proportionally. The index is normalized to 1 with the base-case coefficient values. Tolls are measured on the left-hand axis of Figure 1, and the efficiency index is measured on the right-hand axis. With no congestion, $\tau^O = 0$. The private toll, τ^P, is over \$11 and $r^P = -\infty$. As the congestion index increases, τ^O rises steadily but τ^P actually declines slowly because the congestion charge component in Eq. (8) grows less quickly than the market power components decrease. When the index reaches about 2.1, τ^O and τ^P converge and $r^P = 1$. As congestion increases further, τ^P falls below τ^O, but efficiency declines only slowly (with the index at 3, r^P is still about 0.95).

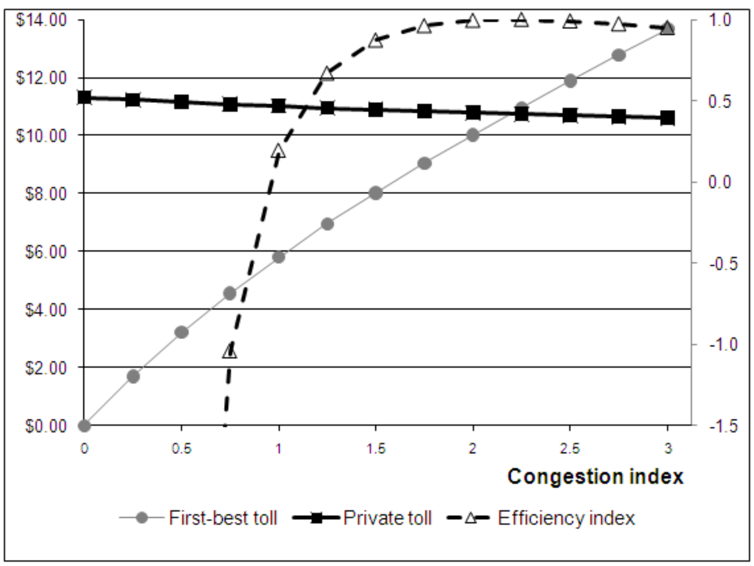

Figure 1: First-best toll, private toll and private efficiency

Further sensitivity results for the three private-toll-road regimes are presented in Table 2. If cars and buses are poorer substitutes (variant 1), the firm has greater market power over drivers, and Regimes *P* and *T* perform less well. Correspondingly, if the two modes are better substitutes (variant 2) these two private regimes perform much better and their efficiency reaches about 80%. Integrated operation (Regime *I*) continues to perform very badly although efficiency moves in the opposite direction to the other two regimes.

Table 2: Efficiency indexes for private market regimes

Private toll-road regime:		Nash (P)	2-stage (T)	Joint (I)
With base case parameters:		**0.194**	**0.211**	**-4.995**
1. Lower mode substitutability	d=\$0.90	-0.027	-0.021	-4.311
2. Greater mode substitutability	d=\$3.60	0.791	0.806	-6.352
3. Higher fixed car cost	$c_0^A = \$7.50$	0.462	0.473	-5.112
4. Lower bus operating cost	k=\$50	0.245	0.261	-5.011
5. Bus PCE for cars & buses=4	$c_n^A = c_n^B = 0.002$	0.171	0.190	-4.983
6. Bus PCE for cars=4	$c_n^A = 0.002$	0.200	0.218	-4.992
7. Two people per car	$c_A^A = c_A^B = 0.00025$	-1.083	-1.039	-9.572
8. Buses more cong. prone	$c_A^B = 0.001$ $c_n^B = 0.002$	0.889	0.892	-1.600

A higher fixed car cost (variant 3) or a lower bus operating cost (variant 4) shifts demand from cars to buses and boosts efficiency for Regimes *P* and *T*, but not Regime *I*. If buses create more congestion (their passenger car equivalent (PCE) is raised from 2 to 4; variant 5) they provide a less efficient alternative to car travel and efficiencies of Regimes *P* and *T* drop slightly. However, if the bus PCE rises only for cars (variant 6) efficiencies are virtually unchanged.

It has been assumed that car travelers drive alone. Multiple car occupancy can be introduced by reducing the coefficients c_A^A and c_A^B. Although most cars can carry 4 adults, peak-period vehicle occupancy in North America tends to 1.2 or less. An intermediate occupancy of 2 is chosen for variant 7. Raising car occupancy effectively reduces the congestion index and (as in Figure 1) efficiencies for all three private regimes drop dramatically. In variant 8, buses are assumed to suffer more from congestion than cars.[13] This variant effectively increases the congestion index. The first-best toll rises toward the private tolls, and all three efficiency indexes rise dramatically.

Together, Table 2 and Figure 1 convey several general lessons. First, Stackelberg leadership for the agency provides little benefit in terms of enhancing market performance. Second, integrated operation performs badly and is probably not worth considering unless tolls and fares can be regulated.[14] Third, the efficiency of private toll road operation is highly sensitive to the substitutability between modes (cf., variants 1 and 2). Fourth, efficiency is also very sensitive to the severity of car congestion. Private operation performs much better when first-best tolls are high (as in variant 8) than when they are low (as in variant 7). Finally, efficiency is not very sensitive to the congestion footprint of individual buses (cf., variants 5 and 6). What matters is the congestion footprint of a passenger, and the footprint is much smaller for large buses than for cars even if a bus contributes several times as much to congestion as does a car.

5. Conclusions and directions for future research

This paper provides a simple, first-cut analysis of private toll roads when traffic congestion is a problem and public transit is a relatively attractive alternative transport mode. The model could be enriched in various ways. Walking and other non-motorized modes could be

[13] This could be because buses need to pull over to the curb to serve bus stops and then re-enter circulation.
[14] Even with effective regulation, integration may not be worthwhile unless tolling roads and providing bus service together creates some kind of synergies.

added as in Anas and Timilsina (2009). Multiple competing modes of public transport can be considered as in Bell and Wichiensin (2008). Bus size can be made endogenous to exploit scale economies of vehicle size as bus ridership increases (Tisato, 2000). These and other extensions are being considered in research under way.

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