CONGESTION PRICING, TRANSIT SUBSIDIES AND DEDICATED BUS LANES: EFFICIENT AND PRACTICAL SOLUTIONS TO CONGESTION

Leonardo J. Basso, Antonio Gschwender
Universidad de Chile, Departamento. de Ingeniería Civil
Casilla 228-3, Santiago, Chile
Fono: 9784380 Fax: 6894206
E-mail: lbasso@ing.uchile.cl, agschwen@yahoo.com

Cristian Angelo Guevara, Marcelo Fuster
Universidad de Los Andes
San Carlos de Apoquindo 2200, Las Condes, Santiago, Chile
Fono: 4129477 Fax: 2149551
E-mail: crguevar@alum.mit.edu, marcelofuster@gmail.com

ABSTRACT

We analyze urban congestion management policies through numerical analysis of a simple model that: allows users to choose between car, bus or an outside option (biking); consider congestion interactions between cars and buses; and allow for optimization of frequency, vehicle size, spacing between stops and percentage dedicated to bus lanes. We find that (i) dedicated bus lanes and congestion pricing deliver close results in terms of social welfare, yet with dedicated lanes consumer surplus is larger increasing the likelihood of raising public support; (ii) without congestion pricing in place, efficient transit subsidies are quite large; establishing dedicated bus lanes or implementing congestion pricing substantially decrease the amount of subsidy required; (iii) in all the settings we analyzed, revenues from congestion pricing are enough to cover transit subsidies; (iv) optimal bus size is smaller than what is usually observed in practice; (v) for the cases we analyzed, the optimal percentage of capacity that should be devoted for bus traffic is around one third; and (vi) if congestion pricing is in place, creating dedicated bus lanes would decrease the optimal congestion tax.

Keywords: congestion pricing, transit subsidies, bus lanes

1. INTRODUCTION

Congestion is, undoubtedly, the externality caused by urban transportation that has attracted the largest share of attention from economists and engineers. The two most popular proposed ways to deal with congestion have been congestion pricing and giving priority to public transportation. Congestion pricing has been analyzed in a very large number of settings such as network equilibrium, and considering all sort of second best issues (e.g. the impossibility of pricing all links); surveys can be found in Small and Verhoef (2007) and Tsekeris and Voβ (2008). A particular feature of the results we would like to stress, is that in most cases, if congestion pricing is implemented, travelers surplus will decrease since the full price consumers pay (time costs plus the tax) is larger than the time costs they pay without congestion pricing. Thus, total social welfare would be increased because tax collection dominates the travelers surplus reduction, making revenue recycling an important issue if political support is to be raised.

On the other hand, many authors have studied the optimal design of scheduled public transport services (Mohring, 1972, Jansson, 1984), seeking frequencies, vehicle sizes, and number and spacing of bus stops that minimize total costs. Although depending on the specific setting, the main result here is that, when one takes into consideration the resources supplied by operators (energy, crew, maintenance, administration, infrastructure, rolling stock and so on) and users (waiting, access and in-vehicle times), the efficient cost minimizing service requires subsidies. This happens because the sum of operators' and users' costs yields a total cost that grows less than proportionally with the demand, implying scale economies; this is sometimes known as *the Mohring effect* (for a review see e.g. Jara-Díaz and Gschwender, 2003).

Now, as it is evident, in most cities people have a choice between using a car or public transportation, and these two modes share road capacity and thus interact with each other. This happens directly on the road, when vehicles are in motion, or when passengers are boarding and alighting in bus stops. In other words, buses delay cars and car delay buses. Yet, as important as this may seem in practice, it has been very uncommon in the literature to consider congestion pricing and optimization of scheduled public transportation in a unique, joint model. Most of the congestion pricing literature deals with cases where only cars are considered, while the public transportation literature do not consider interactions either, nor the fact that buses may impose congestion on other buses if they are too many. Thus, we believe there is an important void that needs to be filled in order to better understand the full implications of different measures targeted at dealing with congestion in cities. Importantly as well, this should help to better assess what may be the level of public support for each of these policies. In this paper we propose a simple tractable model that: (i) allows users to choose between car, public transportation or an outside option (biking) through a discrete choice model (ii) consider congestion interactions between cars and buses (iii) allow for optimization of frequency, vehicle size, spacing between stops and the percentage to be dedicated to bus lanes. We chose the best parameter values possible and simulated the model which enabled a numerically analysis of what would be the outcomes of a number of alternative urban policies such as congestion pricing, allowing for transit subsidies (with or without a constraint on subsidies being covered with revenues from congestion pricing), dedicating a percentage of capacity only for buses, or any combination of these.[1]

[1] A few papers that do consider some of the features we are interested in are Mohring (1972), Small (1983), Viton (1983) and Huang (2000). Yet these models either do not fully consider the interactions between cars and buses, do

2. THE MODEL

We consider a road of infinite length with a capacity of Q vehicles/hour, where Y commuters per kilometer and hour would like to travel l kms (in the same direction). In order to avoid dealing with border conditions, we shall model a representative kilometer of the road. Travel commuters can use one of three modes: car, bus or bicycle, which are chosen in a utility maximization framework. For the two motorized modes we consider congestion externalities caused both by their interaction while in motion, as well as congestion caused by the existence of bus stops. The variables that the planner can (potentially) adjust, and which will obviously affect the utility level of each mode, are: bus frequency, f [bus/h] and bus capacity, K [passengers/bus]; number of equidistant bus stops per kilometer, p; the congestion toll for cars P_a [$/km]; the bus fare P_b [$/trip]; and the percentage of road capacity dedicated exclusively to bus services, η. The possible policies we consider are: congestion pricing, transit subsidies and dedicated bus lanes: the scenarios we analyze are made of combinations of these policies. Obviously, then, some of the variables may not be available to the planner in some of the scenarios.

The utility a commuter perceives, for traveling by automobile (a), bus (b) and cycling (c) are respectively:

$$U_a = Inc + B_a\theta - l\left(SVT \cdot t_a + \frac{(P_a + c_a)}{a}\right) - \frac{g}{a} \tag{1}$$

$$U_b = Inc + B_b\theta - P_b - SVT \cdot \left(lt_b + \frac{\gamma_E}{2f} + \frac{\gamma_{AC}}{2p\nu_{AC}}\right) \tag{2}$$

$$U_c = Inc - SVT \cdot lt_c \tag{3}$$

In each case, the utility of using a mode corresponds to the benefits of undertaking the trip, given here by the daily income Inc [US$/day] plus a modal constant which we will discuss further momentarily, minus generalized costs. These costs include car tolls and bus fares, P_a and P_b; and in vehicle travel times per kilometer, t_a , t_b and t_c, which are multiplied by the Subjective Value of Time, SVT, and the travel distance l. In (1) we also consider operational cost per kilometer, c_a, and parking costs, g, which are shared by the a occupants of a car. In (2) on the other hand, we also consider (average) waiting time, given by $1/2f$, and (average) walking time to and from the bus-stop, given by $1/2p\nu_{AC}$. ν_{AC} [km/h] is walking speed, γ_{AC} and γ_E are the ratios between the in-vehicle SVT and waiting SVT and walking SVT respectively.

Something that is key to capture is the fact that people, even if facing the exact same alternatives, do different things. This users' heterogeneity can be addressed in a number of ways. Here, we have chosen a simple framework: we assume that all commuters share the same value of time and income but differ in their valuation of some other attributes such as safety, comfort, social status and so on. The level of these other attributes are modal specific and captured by B_i in equations (1)-(3). Then, θ is an idiosyncratic term that varies across the population and accounts for the

not allow for optimization of some very relevant variables –such as the percentage of capacity dedicated to buses or bus size– or deals only with minimization of resources, without really considering demand effects.

importance each person assigns to the other attributes. We assume that $B_a > B_b > B_c$, that θ is uniformly distributed in [0;1] and, without further loss of generality, that $B_c = 0$. It is then easy to show that under mild conditions, there exists values of θ characterized by $0 < \theta^b < \theta^a < 1$, which define a modal split where people with value of θ between 0 and θ^b choose cycling, people with value of θ between θ^b and θ^a choose bus, while the remainder choose car – the proof is analogous to the one in Basso and Zhang (2008) for the choice of peak and off-peak travel. Thus, the number of people using each mode is given by:

$$Y_a = Y\left(1-\theta^a\right) \qquad Y_b = Y\left(\theta^a - \theta^b\right) \qquad Y_c = Y\left(\theta^b - 0\right) \tag{4}$$

The values of the θ thresholds can be obtained by equating the utilities. Replacing these in equations (4) and using the fact that $Y_c = Y - Y_a - Y_b$, one can obtain the number of consumers per mode as functions of the variables that the planner chooses, particularly, the congestion toll for cars P_a and the bus fare P_b; in other words, one obtains demand functions. Yet, it happens that is computationally simpler –yet completely equivalent– to describe the optimization problem as one of choosing demand levels Y_a e Y_b (plus the other three variables) rather than prices (plus the other variables). Algebra leads to the following *inverse* demand functions:

$$P_a = \frac{a\left(B_a\left(Y - Y_a\right) + B_b Y_b\right)}{Yl} - \frac{aSVT\left(t_a - t_c\right)l + c_a l + g}{l} \tag{5}$$

$$P_b = \frac{B_b\left(Y - Y_a - Y_b\right)}{Y} - SVT\left(l\left(t_b - t_c\right) + \frac{\gamma_E}{2f} + \frac{\gamma_{AC} l}{2p\nu_{AC}}\right) \tag{6}$$

We can now move on to the central issue of in-vehicle travel time functions. Ideally, one would like to use functions that capture, as close to reality as possible, the effects that the distance between stops, number and size of buses and cars, and available lanes has on the average speed of cars and buses. Yet, we are not aware of any model that proposes this in tractable way and, therefore, we have opted for choosing simple linear forms, which capture the effects we desire yet may be unrealistic if second order effects are strong. Suppose first that buses and cars are physically separated, such that buses can use a proportion η of the capacity Q, while cars use (1-η). The time that a car takes to travel one kilometer will be given by:

$$t_a = \alpha\left(\frac{\frac{lY_a}{a}}{(1-\eta)Q}\right) + \beta \tag{7}$$

where the figure in the numerator corresponds to the flow of cars –since l is the distance of each trip, and a is the number of people per car– and thus show congestion effects. α and β are parameters. Obviously, since in this case buses and cars are not really interacting with each other, there are no cross-congestion effects. On the other hand, the time it takes a bus to travel one kilometer when it has exclusive use of a proportion η of the road capacity is:

$$t_b = \left(\alpha \left(\frac{bf}{\eta Q} \right) + \beta \right) + \frac{Y_b t_{sb}}{f} + t_p p \tag{8}$$

On the right hand side of (8), the first term in brackets represent travel time while the vehicle is in motion: buses, like cars, can suffer from congestion. The flow of buses is multiplied by an equivalence factor b that attempts to capture the differences in size and maneuverability between cars and buses, factor that has usually been assumed to be constant (e.g. Mohring 1979). Here, however, following Gibson, Bartel and Coeymans (1997) we let this parameter be given by $b(K) = 1 + K/100$, where K is the capacity of the bus. In the second term in (8), t_{sb} is the average time that a passenger takes to board and alight the bus, thus this term captures delays for bus stops operations. Finally, the third term captures the fact that, in order to load and unload the bus at a bus stop, the driver has to first stop and later accelerate the vehicle, which causes further delays at a rate of p seconds per stop.

For mixed-traffic conditions, in the absence of a function that, grounded on real data, delivers the effects that the distance between stops, number, size and load factor of buses has on the average speed of cars and buses, we simply consider that a fraction of the extra-time that a bus requires for bus stop operations is also incurred by cars. We set this fraction to one half (since it may be possible for the car to surpass a bus), and thus obtain the travel time for cars in mixed-traffic is:

$$t_a = \left(\alpha \left(\frac{bf + \frac{lY_a}{a}}{Q} \right) + \beta \right) + \left(\frac{\frac{Y_b t_{sb}}{f} + t_p p}{2} \right) \tag{9}$$

Note that in the first term, the capacity is now shared (there is no η) and a bus is treated as b cars. Buses on the other hand, still use time for boarding-alighting operations and acceleration from bus stops, but now they also suffer from congestion caused by cars. Thus, their travel time function in mixed-traffic conditions is as (9), but without dividing the last term by 2.

Finally, the cost of the bus system (in dollars per hour) is given by

$$C_b = (c_{b0} + c_{b1} K) f t_b \tag{10}$$

where the term in brackets represents operational cost per bus and hour, which are larger for larger buses ($c_{b1} > 0$). And since bus capacity may also be optimized, a constraint that ensures that buses are large enough to carry the demand has to be imposed, that is $K \geq Y_b \, l / f$.

3. OBJETIVE FUNCTION, SCENARIOS AND PARAMETER VALUES

We consider that the planner seeks to maximize a social welfare function given by the (un-weighted) sum of consumer surplus plus government revenues (including transit) minus operational transit costs. That is

$$SW = CS + P_b Y_b - C_b + P_a \frac{Y_a}{a} l \tag{11}$$

where consumer surplus is obtained by adding consumers' utilities.[2] What changes from one scenario to the next are the policies that the planner chooses to (or can) implement. These policies are congestion pricing, transit subsidies and dedicated bus lanes and, therefore, the scenarios we analyze are made of combinations of these policies. To start with, in all cases the planner must consider at least three technical constraints. First, there is the constraint of minimal bus size but, since having idle capacity only decreases the objective function, buses will always be chosen to meet demand. On the other hand, the number of commuters in each mode cannot be negative. In summary, the planner must consider:

$$K = Y_b l / f \quad , \quad Y_a \geq 0 \quad , \quad Y_b \geq 0 \quad , \quad Y_a + Y_b \leq Y \tag{12}$$

We can now move to the description of the eight different scenarios we simulate. The first four consider mixed-traffic conditions while the last four consider that the percentage of exclusive capacity for buses, η, is also optimized. The scenarios are as follows:

<u>Scenario 1</u>*: Self-financing transit, no congestion pricing, mixed-traffic*

The first scenario corresponds to the current situation in many cities around the world. It features self-financing for the bus system, no congestion pricing and shared capacity by buses and cars. The problem solved by the planner in this scenario is then:

$$\text{Max}\, SW \quad w.r.t \quad f, p, Y_a, Y_b \quad subject\ to \quad eq.\ (12),\ P_a = 0\ ,\ P_b Y_b \geq C_b$$

<u>Scenario 2</u>*: Transit subsidies, no congestion pricing, mixed-traffic*

In this second case we consider a transit subsidization policy, which here takes the form of no longer asking the transit fare to cover transit costs. In this sense, the subsides are *optimal* (yet how is the money for subsidies raised s not part of this optimization problem):

$$\text{Max}\, SW \quad w.r.t \quad f, p, Y_a, Y_b \quad subject\ to \quad eq.\ (12),\ P_a = 0$$

<u>Scenario 3</u>*: Transit subsidies, congestion pricing, mixed-traffic*

[2] Note that the utilities depend on travel time functions, which in turn depend on optimization variables. Replacing both the utilities and the travel time functions in SW is cumbersome though, so we simply leave it as it is. It is also important to recognize that the travel time functions to be used depend on whether exclusive lanes are considered as a policy or not.

The third scenario, in addition to transit subsidies, considers congestion pricing which, according to the model above, consists of a per-kilometer charge.

$$\text{Max}\, SW \quad w.r.t \quad f, p, Y_a, Y_b \quad subject\ to \quad eq.\ (12),$$

<u>Scenario 4</u>*: Transit subsidies paid for by congestion pricing revenues, mixed-traffic*

In the final scenario with mixed-traffic conditions, what we intend to explore by comparison with scenario 3, is whether optimal transit subsidies can be covered by optimal congestion pricing plus optimal bus fare. In other words, whether imposing a urban transport sector *self-financing constraint* leads to welfare losses or not. The optimization problem is now:

$$\text{Max}\, SW \quad w.r.t \quad f, p, Y_a, Y_b \quad subject\ to \quad eq.\ (12),\ \frac{Y_a}{a} P_a l + P_b Y_b \geq C_b$$

The next four scenarios, 5 to 8, are similar to scenarios 1–4 but now we consider cases where buses enjoy dedicated lanes. The percentage of the (fixed) road capacity that goes to these lanes is optimized continuously:

Scenario 5: Self-financing transit, no congestion pricing, dedicated bus lanes
Scenario 6: Transit subsidies, no congestion pricing, dedicated bus lanes
Scenario 7: Transit subsidies, congestion pricing, dedicated bus lanes
Scenario 8: Transit subsidies paid for by congestion pricing revenues, dedicated bus lanes

Given this, one could think that compared one to one –for example scenario 2 vs. scenario 6–, welfare will be larger in the latter, since there is an additional optimization variable. This is not directly true though, because the travel time functions are now different.

As it is evident, the model we propose to simulate requires a large number of parameters. And while we do realize that our model is a simplifying abstraction, we have chosen to use parameters that represent reality as close as possible. In this sense, almost all parameters –with the exception of parameters B_i– have been obtained or calculated from data that represent a morning-peak in Santiago, Chile, where monetary values correspond to 2006 US dollars. For space reasones we omit here our data sources and calculations and restrict ourselves to present our simulation results, but details are available from the authors upon request. We do comment on the B_i values though: since we did not have direct data for these, and obtaining values from calibrated demand models was not simple, what we did is that we chose the values of Bs such that the modal split in scenario 1 gave us something *reasonable*.

4. SIMULATION RESULTS

All eight scenarios were simulated using the software Wolfram Mathematica to solve the optimization problems. The results of these simulations are presented in Table 1 (at the end of the text); we have also created Figure 1 that summarizes the results of each scenario in terms of the value achieved of Consumer Surplus and Total Social Welfare. The idea with this is to jointly assess the social goodness and the level of public support that each policy may find. For example, a policy that produces an increase in social welfare, but a decrease in consumer surplus, is a policy that may find stronger opposition unless government revenues are *recycled* in some clear and known way. Below, we perform our comparisons of scenarios and through this, of urban transport policies.

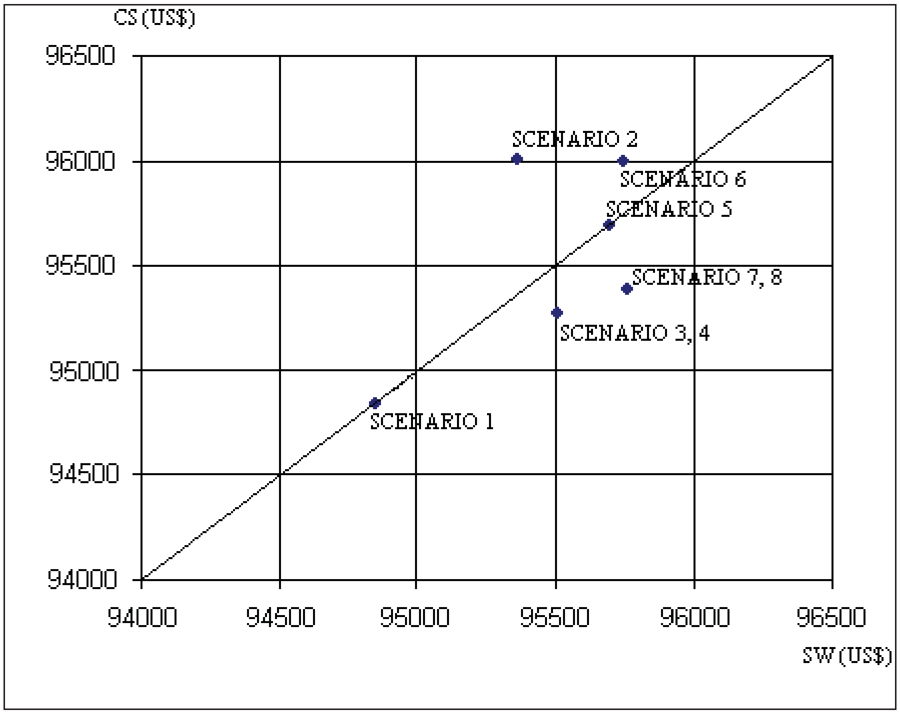

Figure 1: Consumer Surplus and Total Social Welfare

<u>*Effects of Transit Subsidization*</u>

A look at Table 1, specifically a comparison between scenarios 1 and 2, and 5 and 6, shows that transit subsidies is a policy that works, in that it increases total social welfare and consumer surplus (see Figure 1). It also changes the modal split importantly. It is, however, a policy quite expensive for the government: optimally, it may even lead to negative prices. Next, as it has been discussed in the literature (see e.g. Jara-Díaz and Gschwender, 2003), with transit subsidies frequencies and bus size increase. But both phenomena are damped by the existence of dedicated bus lanes.

From Figure 1 it can be noted that, compared to the base case (Scenario 1), transit subsidaition is policy that produces a smaller increase in social welfare than dedicated bus lanes alone. In turn, Transit subsidization is the policy that produces the largest consumer surplus and, therefore, would be the one with the largest public support. When comparing the effect of transit subsidization applied on top of other policies, it can be noted from figure 1 that when applied over dedicated lanes (Scenario 5 to 6), transit subsidization produces an small increase in welfare and a relatively larger increase in consumer surplus. In turn, transit subsidization had no effect when applied over congestion pricing (Scenario 3) since that policy indirectly made the financial result of the bus system to be positive, and therefore, the subsidies to be zero.

Effects of Congestion Pricing

The scenarios that consider congestion pricing are scenarios 3, 4, 7 and 8. The first obvious and expected result of congestion pricing is that it induces a change in the modal split, moving commuters from cars to the transit system, on top of what transit subsidies achieved. Table 1 also reveals that congestion pricing induces an important increase in speeds, in bus frequency and on bus size. Importantly, the use of a congestion pricing policy induces an increase in the bus fare, which now is not only positive but it generate revenues that more than cover costs. The financial result of the transit system is negative again if one considers a smaller total demand (not shown), but there is a clear effect of congestion pricing on reducing importantly the size of transit subsidies. Moreover, if all scenarios are simulated again but with half the total demand, it is always the case that optimal congestion pricing revenues cover optimal transit subsidies.

Figure 1 shows some important other insights. First, it can be noted that congestion pricing applied over the base case (from Scenario 1 to 3) produces an increase in social welfare and, at the same time, an increase in consumer surplus. This contradicts the usual result that consumer surplus decreases with congestion pricing. This occurs because in our analysis, an increase in the cost perceived by car drivers induce larger ridership for transit, which increases its service quality. This is well in line with the *Down's Thomson Paradox* (Mogridge, 1990).

In turn, when congestion pricing is applied on top of transit subsidies (a change from scenario 2 to 3), social welfare increases slightly but consumer surplus decreases importantly. The same effect is observed when congestion pricing is applied on top of dedicated bus lanes (Scenario 5 to 7). The explanation for the reduced marginal effect of the application of congestion pricing comes from the fact that, under optimal subsidization or bus lanes, the number of cars in the street is already small, making unimportant the effect of any additional reduction in car flows.

Mixed Traffic vs Dedicated lanes

What one expects from a policy that assigns part of road capacity to dedicated bus lanes is that bus speed should increase considerably, given that buses are no longer trapped by car congestion. Car speed may increase as well, because cars may now avoid conflict with buses, but decreased capacity for cars may have the opposite effect.

When comparing scenarios 1 and 2, what Table 1 shows is that indeed buses can now go faster – almost three times!– while cars also increased their speed. The large increase in bus speed induces quite an increase in bus frequency, but also bus size increases. All this generate a large increase in bus demand when compared to mixed-traffic conditions. It is interesting to note that the increase in frequency does not require an increase in bus fleet. And with the large bus patronage, revenues are larger which allows a decrease in the bus fare. In other words, dedicated bus lanes decrease everyone's travel times and decrease bus fare. This is shown clearly in Figure 1, where Scenario 5 has larger Consumer Surplus and Social Welfare.

The addition of dedicated bus lanes when a subsidization policy is in place (scenario 2 against 6) has the clear effect of reducing the amount of subsidies required. While the bus optimal fare is still negative, its value is now half what it was under mixed-traffic conditions. This happens because increased speed helps to make the bus system more attractive, so that it is less necessary to use fare. Given this decrease in the subsidy, consumer surplus is slightly smaller, yet the increase in social welfare is sizeable. Next, if from mixed-traffic conditions with subsidies and congestion pricing, the system adds dedicated bus lanes, then both consumer surplus and social welfare increase. In fact, dedicated bus lanes reduce the congestion pricing tax.

Hence implementing dedicated bus lanes seems to be a policy that can improve any existent situation. And in all four cases, the optimal percentage of capacity to be dedicated exclusively to buses is around a third (it varies from 30 to 34%). Given that the capacity we chose roughly correspond to three lanes, our results would imply that one in three lanes should be devoted only to bus traffic.

Congestion Pricing vs. Dedicated Lanes

Mohring (1979) argued that bus speed was one of the most important attributes of the system and that as such, it should be one the central objectives of planners, if they want to increase bus patronage. This is why he considered that dedicating lanes exclusively to bus traffic can be a quite successful policy. Furthermore, he argued that dedicated bus lanes may be a tool equivalent to congestion pricing in achieving a change in modal split. To address this comparison, one has to look at scenarios 3 (or 4) which feature transit subsidies and congestion pricing in mixed-traffic conditions, and scenario 5, where the only policy is dedicated bus lanes (there is no congestion tax and buses have to self-finance). Figure 1 gives us a clear picture: dedicated bus lanes achieve both larger consumer surplus and larger total social welfare. And note that in scenario 4, there is no cost to the government in that congestion pricing revenues more than cover transit subsidies.

The possible implications of this lie in policy making: the benefits of dedicated bus lanes go directly to bus passengers and do not require revenue recycling, as opposed to congestion pricing. Hence, dedicated bus lanes may be a transit prioritization policy that may find less opposition that a congestion pricing policy, as long as car congestion is tolerable.

5. SUMMARY AND CONCLUSIONS

People have a choice between using a car or public transportation, and these two modes share road capacity and thus interact with each other. This happens directly on the road, when vehicles are in motion, or when passengers are boarding and alighting in bus stops. Yet, as important as this may seem in practice, it has been very uncommon in the literature to consider congestion pricing and optimization of scheduled public transportation in a unique, joint model. Most of the congestion pricing literature deals with cases where only cars are considered, while the public transportation literature do not consider interactions either, nor the fact that buses may impose congestion on other buses if they are too many.

This paper deals exactly with this issue, by proposing a simple tractable model that: (i) allows users to choose between car, public transportation or an outside option (biking) through a discrete choice model (ii) consider congestion interactions between cars and buses (iii) allow for optimization of frequency, vehicle size, spacing between stops and the percentage to be dedicated to bus lanes. Analyses of numerical simulations of the model allowed us to better see the full implications of different measures targeted at dealing with congestion in cities –such as congestion pricing, transit subsidies or dedicated bus lanes–, as well as to explore what may be the level of public support for each of these policies.

Our results show, among other things, that: (i) dedicated bus lanes and congestion pricing, deliver close results in terms of social welfare, yet with dedicated lanes consumer surplus is larger, increasing the likelihood of raising public support; (ii) without congestion pricing in place, efficient transit subsidies are quite large since in many cases the efficient transit price is negative; establishing dedicated bus lanes or implementing congestion pricing substantially decrease the amount of subsidy required; (iii) in all the cases and settings we analyzed, revenues from congestion pricing are enough to cover the transit subsidies required; and (iv) for the cases we analyzed, the optimal percentage of capacity that should be devoted for bus traffic is around one third.

REFERENCES

Basso, L. and Zhang, A. (2008) Sequential Peak-load Pricing: The Case of Airports and Airlines, **Canadian Journal of Economics**, 41(3), 1087-1119.

Gibson, J., Bartel, G., Coeymans, J.E. (1997) Redefinición de los Parámetros de Capacidad de una Intersección Semaforizada bajo Condiciones de Tráfico Mixto. **Actas del VIII Congreso Chileno de Ingeniería de Transporte**, Santiago.

Huang. H-J. (2000) Fares and Tolls in a Competitive System with Transit and Highway: the case with two groups of commuters. **Transportation Research Part E**, 36, 267-284

Jansson. J.O. (1984) **Transport System Optimization and Pricing**. Wiley.

Jara-Díaz. S.R. and Gschwender. A. (2003) Towards a general microeconomic model for the operation of public transport. **Transport Reviews**, 23, 453–469

Mohring. H. (1972) Optimization and Scale Economies in Urban Bus Transportation. **American Economic Review**, 62, 591–604.

Mohring. H. (1979) The Benefits of Reserved Bus Lanes. Mass Transit Subsidies and Marginal Cost Pricing in Alleviating Traffic Congestion. In **Current Issues in Urban Economics**. Mieskowosky. P. y Straszheim M. editors.

Mogridge, M (1990) **Travel in towns: jam yesterday, jam today and jam tomorrow?** Macmillan Press, London

Small. K. (1983) Bus Priority and Congestion Pricing on Urban Highways. In **Research in Transportation Economics**. Keeler. T. Ed. JAI.

Small. KA. and Verhoef. ET. (2007) **The Economics of Urban Transportation**. London. Routledge.

Tsekeris. T. and Voβ. S. (2008) Design and Evaluation of Road Pricing: state-of-the-art and methodological advances. **Netnomics**, 10(1), 5-52.

Viton. P. (1983) Pareto Optimal Urban Transportation Equilibria. In **Research in Transportation Economics.** Keeler. T. Ed. JAI.

Table 1: Results of numerical simulations of scenarios

	Scenario 1	Scenario 2	Scenario 3	Scenario 4	Scenario 5	Scenario 6	Scenario 7	Scenario 8
Number of stops per km.	2.663	2.449	2.678	2.678	2.779	2.779	2.784	2.784
Car demand [pax Km.]	249.725	130.210	27.179	27.179	147.494	127.336	103.175	103.175
Bus demand [pax Km.]	79.966	206.210	307.444	307.444	187.512	209.084	231.328	231.328
Bicycle demand [pax Km.]	6.730	0.000	1.797	1.797	1.414	0.000	1.917	1.917
Total Operational Cost of Cars [US$]	2076.794	1082.866	226.030	226.030	1226.611	1058.965	858.035	858.035
Total Operational Cost of Buses [US$]	50.314	73.858	66.637	66.637	35.923	39.275	42.873	42.873
Financial Result of Bus system [US$]	0.000	-648.362	65.384	65.383	0.000	-253.876	90.386	90.386
Congestion pricing revenues [US$]	0.000	0.000	169.386	169.386	0.000	0.000	282.674	282.674
Congestion Pricing Fee [US$]	0.000	0.000	0.935	0.935	0.000	0.000	0.411	0.411
Bus fare [US$]	0.629	-2.786	0.429	0.429	0.192	-1.026	0.576	0.576
Total trip time: car [hrs.]	0.080	0.054	0.031	0.031	0.063	0.055	0.049	0.049
Total trip time: Bus [hrs.]	0.088	0.062	0.040	0.040	0.037	0.038	0.038	0.038
Total trip time: Bicycle [hrs.]	0.083	0.083	0.083	0.083	0.083	0.083	0.083	0.083
Car speed [Km./hrs.]	12.482	18.497	31.921	31.921	15.963	18.114	20.354	20.354
Bus speed [Km./hrs.]	11.371	16.064	25.234	25.234	27.047	26.397	26.526	26.526
Bicycle speed [Km./hrs.]	12.005	12.005	12.005	12.005	12.005	12.005	12.005	12.005
Bus frequency [Bus/hrs.]	33.755	60.770	82.651	82.651	45.503	46.495	50.548	50.548
Bus capacity [pax]	28.428	40.720	44.638	44.638	49.451	53.963	54.917	54.917
Bus fleet [Buses Km.]	2.969	3.783	3.275	3.275	1.682	1.761	1.906	1.906
Car-bues equivalence [cars]	1.284	1.407	1.446	1.446	1.495	1.540	1.549	1.549
Consumer Surplus [US$]	94847.836	96005.155	95271.204	95271.204	95688.505	95994.154	95385.636	95385.636
Total Social Welfare [US$]	94847.836	95356.793	95505.973	95505.973	95688.505	95740.278	95758.696	95758.696
Porcentage of dedicated lanes [%]					31.369	30.426	34.278	34.278