URBAN ROAD CAPACITY INVESTMENTS AND THE DOWNS-THOMSON PARADOX

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ABSTRACT

We study the effects of road capacity investment in a setting with imperfectly elastic travel demand and where public transport and car travel are substitutes and cross- congest each other. We simulate the model using data for London, UK. We analyze its efficiency and see how it is affected by and compares to other policies such as bus lanes, congestion pricing, and transit subsidization. We have shown that the Downs-Thomson paradox, in its most simple form, is not likely to hold when the mode choice model allows for generalized costs differences in equilibrium, as is the case with most of the models used in practice. In a nutshell, generalized costs did not increase in equilibrium after road expansion. We further showed the importance of realistically modeling bus stop operations: depending on the capacity of the bus stop, even bus riders may benefit from road capacity investments. We also studied the efficiency of capacity expansions, comparing it to the welfare gains of the other possible policies. We found that, while road expansion is indeed welfare improving, it has a limited overall scope to be chosen in a strict cost-benefit analysis framework; it would only when congestion both for cars and buses is very strong, and when investment costs are low, possibly because no expropriation is needed.

1. INTRODUCTION

Urban congestion is, undoubtedly, one of the main problems that inhabitants of large cities have to suffer; studying ways of dealing with it is important then, and it is so, for several reasons:

1) Travel times increase with congestion, something that people dislike and that taxes quality of life. For example in 2001 an average US household spent 161 person- minutes per day in a passenger vehicle. In Santiago, in 2012, more than 30% of people from the poorer parts of the city spent more than 60 minutes in buses to arrive to their jobs, travel time explained by increasing car congestion.

2) Both congestion and infrastructure costs are very large and therefore, both should be accurately assessed before implementing any large construction project. The real benefits of new urban highways, expensive subway lines or BRT systems have to be realistically evaluated and compared against the best possible alternative which sometimes may involve pricing out part of the traffic, or reallocating capacity to specific modes in dedicated fashion.

3) Congestion implies many engines at work at the same time, for long periods of time, which in turn implies increasing levels of emissions. Estimations for both Canada and the UK have shown that 25% of GHG emissions are provoked by the transportation sector. And according to the US Bureau of Transportation Statistics the road transportation sector accounts for about a third of US carbon emissions from energy use.

Proposed solutions to the congestion problem can be divided into two types, if we stay away from those that attempts to directly affect location decisions: (i) better use of existing capacity (ii) more capacity.

Regarding the first idea, the usual propositions are congestion pricing and giving priority to public transportation: the first, because it follows the Pigouvian tradition of charging for the external costs produced by an agent's decision; the second, because public transportation provides a mean of transporting more people using less space, thus diminishing congestion. Congestion pricing has been analyzed, in only car models, in a very large number of settings. References can be found in Small and Verhoef (2007) and Tsekeris and Vob (2009). Giving priority to public transportation usually means that an optimized service should be subsidized and/or be granted dedicated capacity. Basso and Silva (2014) analyze these ideas in a bimodal system, studying the efficiency and substitutability of transit subsidies, dedicated bus lanes and congestion pricing; a full set of previous references can be found there.

The second proposed solution to the urban congestion problem is, after all, perhaps the most natural one: if existing capacity is not enough for actual traffic, then increase capacity. In short, if your shoes no longer fit, buy larger shoes. In Chile, the idea used to justify building urban highways in the 1990s was "infrastructure deficit", something that was calculated by comparing the change in car ownership to the change in road kilometers. But this is again, very controversial, at least in academic circles (it seems to be less for Governments and politicians), because it has been argued that roads cause traffic and that every kilometer made available to cars in a congested city will be filled up with new traffic. In a sense, then, building more capacity is simply feeding the problem: is like trying to battle obesity by buying larger belts. Which view is

correct? Our paper deals exactly with this, by attempting to answer two research questions: Does urban road capacity expansion lead to lower travel generalized costs? And, how efficient is this policy and how does it interact with the other policies to reduce congestion?

The existing literature on the 'self-defeating nature of road capacity investments' dates back to Downs (1962) and Thomson (1977), and something that is today known as the Downs-Thomson paradox (as presented by Mogridge, 1997). The essential idea behind the paradox is that more car capacity will lure people out from public transportation, which will then need to decrease its quality of service because of reduced ridership, particularly density of routes and frequencies. This will again push people from transit to private cars, inducing more congestion and a worse public transport system; and overall worse situation caused by induced traffic. The Downs-Thomson paradox and can be graphically explained as in Figure 1. In panel (a), gA represents the generalized cost of automobile travel for one driver. Because of congestion, it increases with the number of cars. On the other hand gT is the the generalized cost of transit travel for one user. It would diminish with the number of users because of the *Mohring effect*, that is, increased ridership induces an increase in frequency, which diminishes waiting times of all users. If total demand for travel is Y, then the Downs-Thomson *hypothesis* establishes that the intersection will determine the modal split, since no consumer can unilaterally diminish his own travel time. An increase in road capacity will shift the congestion curve so that for the same number of drivers, the generalized cost is smaller. But that would induce people to leave the public transport system, leading to a new equilibrium which is worse than before.

(a)   (b)
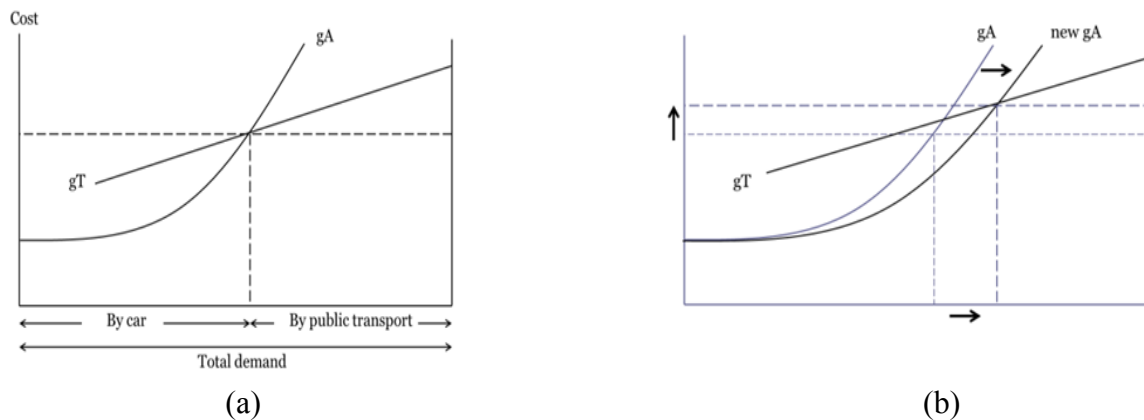
Downs-Thomson Paradox. **Figure 1**

Detractors, though, argue that the causal relation road-traffic is unclear, that transit systems do get congested (making the gT curve take an upward trend after a while) and that the same argument –taken to the extreme– would prescribe no capacity for cars whatsoever, something unreasonable altogether. In fact, the actual practice show that in most cities, there is always some increase in road capacity going on ¿are all of those inefficient?

Clarifying whether the Downs-Thomson hypothesis is correct or not or, more precisely, in which circumstances is an accurate description of the outcome, is fundamental for urban public policies and quality of life in cities. If right, it would imply that policies targeted at increasing road

capacity will worsen the problem, while using space that is scarce and that can be devoted to many other useful alternatives. If wrong, it would imply that what has been argued by many transport engineers has been equivocal, and that cities can build their way out congestion indeed. Our claim is that the question "Is road capacity expansion a self-defeating policy?" cannot be precisely answered with what the literature has given us so far, because there are three relevant aspects of the problem that have not been well incorporated in the theoretical and the empirical literature.

The first issue is that, as explained by Basso and Jara-Díaz (2012), the Downs- Thomson paradox as described by Mogridge (1997) has two important limitations. (1) the transit design (i.e. frequency and vehicle capacity) is not explicitly incorporated, such that optimal transit design – which has an effect on demand– remains hidden behind the shape of the transit generalized costs. (2) the mode choice implicit behind the equilibrium is of the all-or-nothing type: if the generalized cost of one mode is smaller than the other, then everyone will choose that mode and vice-versa. Yet, users also consider mode attributes other than price and time, such as environmental impact or social status. These attributes, together, may represent some form of intrinsic mode attractiveness, which differ across the population, making the number of users of one mode diminish smoothly as its generalized cost grows farther away from that of the other mode (something that popular mode choice models do capture, as the binomial Logit). Basso and Jara-Diaz (2012) include improvements in that direction, but they are used only to study, in depth, congestion pricing and transit optimization and subsidies together. They do not analyze really analyze road expansions although they conjecture that, at least for cars, the Paradox may not hold if more realistic mode choice models are used. We tackle this directly.

The second issue is mixed traffic –where cars and buses congest each other– something that prevails in most cities and that is not included in the Downs-Thomson paradox (and Basso & Jara-Díaz, 2012, do not consider either). Kutzbach (2009) theoretical piece do consider both mixed traffic and separated conditions finding that increasing capacity will always benefit both modes, i.e. the Paradox would not hold. However, in that model an increase in road capacity reduces bus travel time more than car travel time always, by construction, something that is probably not a good assumption to study the effects of capacity investment. Our main point here is that the travel time in the bus system depends crucially on bus stop operations which, we will show, play a key role as they are the main bottleneck of a transit system.

The third issue, which flows from the previous two, is that there has been little analysis of the interaction of a capacity expansion policy with other policies; and investing in capacity when the existing capacity is not priced correctly or when the transit system is not optimized is evidently inefficient. We tackle this following the approach of Basso and Silva (2014).

Sometimes, a variation of the Downs-Thomson paradox receives the naming of "the fundamental law of road congestion". The variation here is that, as opposed to the Downs-Thomson paradox, longer run effects are considered, such as people relocating, changing routes or taking different choices regarding travel altogether.

One of the latest efforts to empirically test whether the law holds or not, which used a rich data set and advanced econometric techniques, is Duranton and Turner (2011). They found that increasing lane kilometers of interstate highways leads to a proportional increase of vehicle-

kilometers travelled, and found similar evidence for major urban roads. It suggests that investing in capacity would not help relieving congestion. Importantly, their analysis aggregates space and time of day and makes no distinction between increasing capacity of current roads or extending the length of the roads. Our analysis is different from theirs in two aspects. First, it is somewhat shorter run, as we will remain within the framework of the "paradox" rather than that of the "fundamental law" but, the flip side is that we will be able to analyze and compare more policies and their interaction and, importantly, perform welfare analyses.

The rest of the paper is as follows: Section 2 presents the model and the data used to simulate it; we attempt to use close to real conditions for London, UK. Section 3 analyses the exact conditions under which the Downs-Thomson paradox holds. In Section 4 we perform welfare analysis, thus comparing the efficiency of dedicated bus lanes, transit subsidization, congestion pricing and road capacity expansion. Section 5 concludes.

2. THE MODEL AND PARAMETER VALUES

2.1 The Model

In this section we briefly describe the analytical model highlighting its key aspects. An in-depth description can be found in Basso and Silva (2014).[1] We model a representative kilometer of the road network of a city where bus service is offered, and we look at one day of operation. Travellers choose whether to travel in one of the two possible periods –peak and off-peak– or not to travel at all; furthermore, if they do travel, they choose between the two modes available in both periods: car and bus. Choices are modelled through a nested logit (see Ben-Akiva, 1973; and Anderson and de Palma, 1992) whose nest structure is depicted in Figure 2.

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[1] The exposition here draws from Basso and Silva (2014). Literal quotes are not made explicit in this Section.
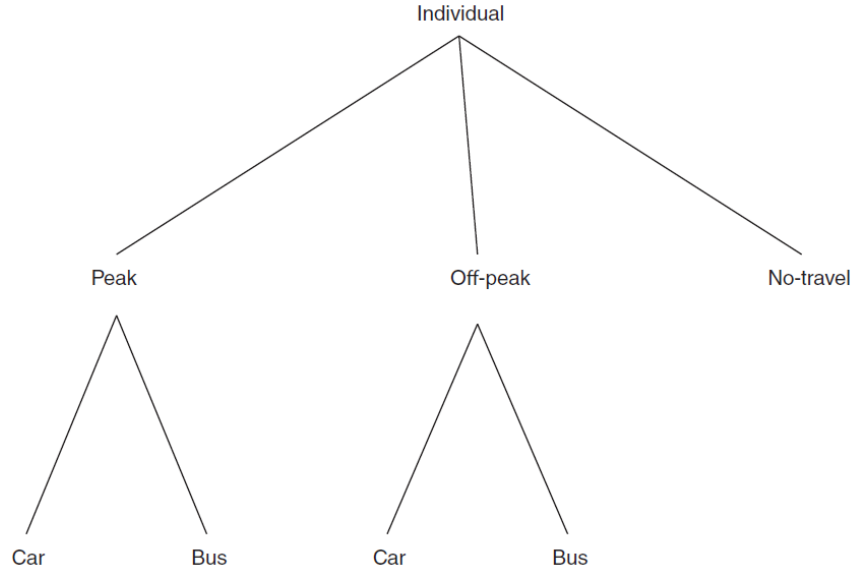
Commuter decision tree. **Figure 2**

The demand model relaxes the assumptions underlying the Downs-Thomson paradox in that the mode choice is not deterministic –i.e. it does not necessarily, equate generalized costs–, there are multiple periods and the period total demand is not perfectly inelastic. It, therefore, allows for assessing its validity in a more realistic setting.

The generalized cost of each mode in each period is the sum of the monetary costs (fare for bus users and operating costs and tolls for car users) and time costs. For buses, time costs are a weighted sum of waiting time, walking time (to and from the bus stop) and in-vehicle travel time, while for cars only in-vehicle travel time is relevant. Travel times are different both when bus and car traffic are segregated and when it is mixed. We explain both separately.

  • Segregated traffic

The time that a bus takes to travel one kilometer, when dedicated bus lanes are in place, in period *q* is given by:

$$t_{bus}^q = t_f \cdot \left(1 + \alpha \cdot \left(\frac{f^q \cdot b(k)}{n \cdot C}\right)^\beta\right) + p \cdot \left(\frac{Y_{qb}}{H^q \cdot f^q \cdot p} \cdot t_{sb} + t_d\right) \qquad (1)$$

The first term on the right-hand side is the time that a bus spends while in motion. The free-flow travel time is t_f, α is a parameter related to speed reductions caused by congestion, f^q is bus frequency in period q, $b(k)$ is an equivalence factor between buses and cars which increases with bus size, C is the capacity of the road (in cars/hour), n is the fraction of capacity dedicated only to buses, and β is a parameter. This flow congestion function is commonly used in transportation analyses. The second term on the right-hand side of (1) is the time spent at bus stops, and it is given by the number of stops that a bus makes in each kilometer, p, multiplied by the time spent at each bus stop. The time each passenger takes to board a bus is t_{sb} and the number of

passengers boarding a bus at each stop is $\frac{Y_{qb}}{H^q \cdot f^q \cdot p}$, i.e. the period bus demand per kilometer, divided by the number of hours in the period, H^q, the bus frequency in the period, and the number of bus stops per kilometer.[2] Finally, t^d is a non-linear function estimated by Tirachini (2014) representing bus stop congestion, that is, buses decelerating, queuing to get in and out of the bus stop and accelerating after alighting and boarding took place. It depends on several variables including bus frequency, bus stop capacity (number of berths), payment method (e.g. cash or magnetic card), boarding procedure (e.g. front door or all doors), number of passengers boarding and so on.

The travel time for a car driver in segregated traffic is:

$$t_{car}^q = t_f \cdot \left(1 + \alpha \cdot \left(\frac{l \cdot Y_{qc}/(H^q \cdot a)}{(1-n) \cdot C}\right)^\beta\right) \tag{2}$$

where $l \cdot \frac{Y_{qc}}{H^q \cdot a}$ is the car flow, since Y_{qc} is car demand per period per kilometer, H^q is the period duration in hours, l is the trip length, a is the (constant) car occupancy and $(1-n) \cdot C$ the capacity they have available.

- Mixed traffic

In mixed traffic conditions we account for the delays that buses cause to cars and that cars cause to buses while both are in motion, but we also consider the delay that bus stop operations cause on cars by adding to the car travel time a fraction ε of the time a bus spends at a bus stop. We make this fraction a function of frequency, such that when f^q goes to zero. ε is 0 and grows until reaching 1 when f^q is very large. In this way we model that cars can overtake buses but this becomes more difficult as there are more buses on the street. The new travel times for each period q are given by:

$$t_{bus}^q = t_f \cdot \left(1 + \alpha \cdot \left(\frac{l \cdot Y_{qc}/(H^q \cdot a) + f^q \cdot b(k)}{C}\right)^\beta\right) + p \cdot \left(\frac{Y_{qb}}{H^q \cdot f^q \cdot p} \cdot t_{sb} + t_d\right) \tag{3}$$

$$t_{bus}^q = t_f \cdot \left(1 + \alpha \cdot \left(\frac{l \cdot Y_{qc}/(H^q \cdot a) + f^q \cdot b(k)}{C}\right)^\beta\right) + \varepsilon \cdot p \cdot \left(\frac{Y_{qb}}{H^q \cdot f^q \cdot p} \cdot t_{sb} + t_d\right) \tag{4}$$

[2] Here we assume that per-passenger boarding takes more time than per-passenger alighting.

- Bus operating costs

We model the operating costs of the bus system (G, in \$/day) as a function of the bus fleet (B), the total number of vehicle-kilometers of each period V_q and the bus size (k) as follows:

$$OC_b = G_b(k) \cdot B + \sum_q G_v(k) \cdot V_q \qquad (5)$$

The first-term on the right hand side is mainly labor and vehicle-capital expenses while the second captures operational expenses. Both types of expenses are a function of the vehicle size through the (linear) functions G_b and G_v, that give the cost per bus per day and cost per vehicle-km respectively.

- Optimization problem

We consider non-weighted social welfare as the objective function, for one kilometer of a day of operation. It is the sum of consumer surplus CS,[3] the financial result of the bus system, congestion pricing revenues minus implementation costs of any policy in place:

$$SW = CS + \left[\left(\sum_q Y_{qb} \cdot P_{qb} \cdot l \right) - OC_b + \left(\sum_q Y_{qc} \cdot P_{qc} \cdot l/a \right) \cdot (1 - \eta) - OC_{dl} - C_{cap} \right] \cdot mcpf$$

where OC_{dl} is the additional cost of implementing and operating dedicated bus lanes with respect to the case of mixed traffic (i.e. it does not include road construction), C_{cap} is the cost of increasing capacity beyond the reference case, η is the fraction of the car congestion pricing revenues that is assumed to be its costs, and $mcpf >1$ is the marginal cost of the public funds.

In this paper we make two types of analyses. First, we assess the validity of the Downs-Thomson paradox in close-to-real conditions, that is, we look at generalized costs before and after road expansion for both transport modes. Second, we study the efficiency of a road capacity expansion policy and compare it with that of bus lanes, congestion pricing and transit subsidization to investigate the complementarities (or lack thereof) between them. To meet these objectives and in order to compare service levels and benefits of the different transport policies, we build scenarios defined as the maximization of social welfare subject to different constraints. There are technical constraints that apply to all scenarios (non-negativity of variables, bus capacity constraints, etc.) and specific constraints that model the existence or absence of specific transport policies and road capacity expansion. We explain these constraints, on a case- by-case basis, in detail below.

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[3] Consumer surplus in the nested-logit model is obtained through what is known as the logsum formula. See Ben-Akiva (1973) and Anderson and de Palma (1992).

For the main analysis of the Downs-Thomson paradox we use the following scenario in which traffic is segregated:

- Dedicated bus lanes (DL)

In this scenario the bus system is self-financed, there is no bus fare differentiation between periods, there is no congestion pricing and the fraction of capacity that is dedicated to buses is set such that buses always have one lane. The travel time functions that are used are (1) and (2). This scenario sets the problem to:[4]

$$Max_{f^p, f^o, P_{pb}, P_{ob}, Y_{pb}, Y_{pc}, Y_{ob}, Y_{oc}, Y_{nt}} \; SW$$

$$s.t. \quad \sum_q Y_{qb} \cdot P_{qb} \cdot l = OC_b \; ; \; P_{pb} = P_{ob} \; ; \; P_{qc} = 0 \; \forall q$$

The capacity of the road is exogenous. To study the effects of road expansion we simply compare the outcome of the maximization of this problem (e.g. mode-specific generalized costs) under two different total capacities. In order to study the impact of the bus system capacity and technology on the results, we can also exogenously vary the payment method, the number of berths of the bus stop and the door operations for boarding and alighting through the bus stop delay function. This way we can assess whether results are specific to particular bus system characteristics or more general. The rest of the scenarios are as follows:

- Reference scenario (REF)

This reference scenario is very similar to the DL scenario: there is no congestion toll, the bus system is self-financed and the bus fare is the same for both periods. The only difference is that the road is shared by buses and cars, meaning that the travel time functions that are now used, and which enter the objective function SW, are equations (3) and (4): constraints do not change. This is a useful reference point to then obtain the incremental benefits of implementing transport policies.

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[4] Demands are optimization variables variables because we impose the equilibrium (fixed-point equation) as a constraint: the number of people that choose each alternative has to be consistent with the mode split equilibrium.

- Transit subsidization (SUBX)

This scenario allows for an X percent of subsidization of the bus system, which translates in a change of the budget constraint. We maintain the constraint of charging the same bus fare during the day, therefore the problem is:

$$Max_{f^p, f^o, P_{pb}, P_{ob}, Y_{pb}, Y_{pc}, Y_{ob}, Y_{oc}, Y_{nt}} \; SW$$

$$s.t. \quad \sum_q Y_{qb} \cdot P_{qb} \cdot l = OC_b \cdot (100 - X)/100 \; ; \; P_{pb} = P_{ob} \; ; \; P_{qc} = 0 \; \forall q$$

- Car congestion pricing (CON)

The implementation of a congestion pricing policy in isolation is represented by this scenario. It is as in the reference case (REF), but without imposing that the car toll is zero.

$$Max_{f^p, f^o, P_{pb}, P_{ob}, Y_{pb}, Y_{pc}, Y_{ob}, Y_{oc}, Y_{nt}} \; SW$$

$$s.t. \quad \sum_q Y_{qb} \cdot P_{qb} \cdot l = OC_b \; ; \; P_{pb} = P_{ob} \; \forall q$$

The rest of the scenarios are simply combinations of the ones described above. For example, to compare the efficiency of a road capacity expansion policy with optimal car congestion pricing we compute the value of the objective function solving REF for a certain capacity, solving CON for the same capacity and the maximum welfare in REF with an increased capacity. By subtracting the first value to the others we obtain the social benefit of the policies. In the same way, we can compare the policies in isolation and all the possible combinations. The results are in Sections 3 and 4.

2.2 Parameter Values

We solve each optimization problem numerically, using data for London. The parameters we use are presented in Table 1 and a brief explanation of how they were obtained follows; a detailed discussion can be found in Basso and Silva (2014). The main data sources are publications from Transport for London (2007) and parameters used by Parry and Small (2009) and reported by Litman (2012).

General parameters	
Reference peak passenger load [pax/hr]	7000
Trip length [km]	9.6
Passenger car equivalence factor for buses $b(k=80)$	2.06
Car operating cost [$/km]	1.187
Car occupancy [pax/car]	1.41
Initial Road capacity (3 lanes) [veq/hr]	3600
Peak duration [hours]	6
Off-peak duration [hours]	14
Demand parameters	
Nested logit scale parameter μ	0.25
Value of peak car travel time [$/hr]	11.56
Value of peak bus travel time [$/hr]	13.88
Value of off-peak car travel time [$/hr]	9.25
Value of off-peak bus travel time [$/hr]	11.10
Waiting time weight in generalized travel time	2.00
Walking time weight in generalized travel time	2.50
Transport time parameters	
Free flow speed [km/hr]	60.0
Boarding time (cash payment, front door boarding, 3 door bus) [seconds/pax]	4.0
Boarding time (magnetic card payment, front door boarding, 3 door bus) [seconds/pax]	11.8
Walking speed [km/hr]	3.6
Fraction of bus interval for waiting time.	0.5
Bus parameters	
$G_h(k=80)$[$/vehicles-day]	1155
$G_v(k=80)$[$/vehicles-km]	2.40
Welfare function parameters	
Marginal cost of public funds	1.15
Congestion pricing operational cost [share of revenues]	0.45
Dedicated bus lanes operational cost [$/km]	73.71

Parameter values. **Table 1**

The base road capacity and passenger load are chosen to generate a congested peak period in absence of policies (REF scenario). The demand parameters are obtained using the elasticity of car-peak demand with respect to car-peak travel time (Litman, 2012), the observed car share of trips (Transport for London, 2007), the travel times from average traffic speeds (Transport for London, 2007), and the values of travel time savings (U.K. DfT, 2009). The scale parameter μ and the expected utility of no-travel are set such that: (i) our implied elasticity of total travel demand with respect to the peak bus fare in the reference scenario is similar to the one implied by Parry and Small (2009) in their reference scenario (i.e. -0.002); and (ii) that our implied elasticity of bus peak demand with respect to bus peak fare, –0.25, is similar to the one reported by Litman (2012) and the one used by Parry and Small (2009), that is, –0.24 and –0.4 respectively. Finally, the modal constants of the nested logit model are calibrated simply by imposing that the observed

modal share (adjusted for a two mode system in each period) is equal to the one that the model predicts with the observed values of each attribute.

The data for bus operating costs is from Basso and Silva (2014), which is estimated using data from Santiago, Chile and adjusted to account for differences in input costs (including energy, labor and capital). The marginal cost of public funds is set to 1.15 following Parry and Small (2009). The share of congestion pricing revenues that is spent operating the system is set to the average of the reported values by Transport for London for the period 2004-2008. The cost of operating dedicated bus lanes is estimated by Tirachini et al. (2010) for Australia, and it includes the operation and maintenance of track, right-of-way, signaling, communications and so on.

3. DOWNS-THOMSON PARADOX

To assess the validity of the Downs-Thomson paradox in our setting, we solve the welfare maximization problems for each policy in isolation in two different road capacity situations, and compare optimal values. In particular, we are interested in the resulting car and bus generalized costs, because, as explained in the introduction, the Paradox states that "in congested conditions the equilibrium travel costs will rise if road capacity is increased, if the cost of travel on the collective network rises as flow falls. It follows that increasing road capacity in congested conditions is counterproductive" (Mogridge, 1997, p. 9). This way, we can study what happens when road capacity is expanded under different initial situations: with or without optimal congestion pricing in place, with or without transit subsidies, with or without dedicated bus lanes.

We start with separated traffic since in the Downs-Thompson paradox that seems to be the implied idea. We start from our REF case (self-financed bus system, no subsidies or congestion pricing) and maximize welfare for a three lanes road (one for buses, two for cars) and then consider consecutive expansions of one additional lane for cars. We initially consider bus stop operations where payment is made in cash to the bus driver, there is only one berth and boarding occurs only through the front door. The initial equilibrium situation in the peak is quite congested, with car speed being 13 km/hr and bus speed being 11 km/hr; modal shares are close to equal. In the off-peak, car speed increases importantly while bus speed does not change as much; the modal split tilts significantly towards private transport.

We first observe that per period demands do not change much: peak demand increases by 1.49 percentage points (*pp* from now on), off-peak demand decreases by 1.11 pp while no travel decreases by 0.38 pp. Thus, even though the modeling is done for a full day and considering inter-temporal demand elasticities, we can present our results per period with the assurance than nothing large is being missed. In the next table we show how generalized costs change when the first car lane is added.

	Road Capacity [veq/hr]	
Peak Period	3 lanes	4 lanes
Car	3.050	2.527
Bus	1.546	1.511
Off-peak Period	3 lanes	4 lanes
Car	2.040	1.922
Bus	1.206	1.217

Generalized peak and off-peak costs after a one lane road expansión. **Table 2**

What these results show is that, in the peak, both modes *diminish* their generalized costs; the paradox does not hold. In the off-peak car users are still better off by the road expansion, while bus users are slightly worse off, so the paradox would hold only partially. Modal split changed by 5 pp in the peak and by 3 pp in the off-peak.

Why is it that the Paradox does not hold? We conjecture that two reasons may be in place. The first is the one highlighted by Basso and Jara-Díaz (2012): in the Downs- Thompson paradox, the demand model (implicitly) assumes that generalized costs are equal, something sometimes known as the Downs-Thomson Hypothesis.[5] But if the demand model is such that this is not the case, then it could happen that car drivers improve their situation after a road expansion, while bus riders end up being worse. This could happen because the gap between generalized costs may decrease, together with a decrease in the generalized cost of car travel and an increase in the bus travel's. But in Basso and Jara-Díaz bus riders always find themselves in a deteriorated situation, which here is the case in the off-peak but not in the peak. Our conjecture is that, as opposed to what is assumed in the graphical explanation of the Downs-Thompson paradox, the public transport cost curve may not be decreasing always: if bus stop operations are quite congested, the cost curve may very well be upward sloping.

In order to explore these conjectures we run our simulations again, considering this time four types of bus stop capacity:

- Low-capacity: payment in cash, 1 berth, boarding through front door only,
- Medium-capacity: payment through contactless card, 2 berths, boarding through front door only,
- High-capacity: payment through contactless card, 3 berths, boarding through all doors
- Infinite capacity: small constant boarding time irrespective of conditions + no congestion in the bus lane.

We also consider, additionally, a deterministic demand model. Our generalized cost and modal split results for the peak-period and a low-capacity bus stop, as three lanes are successively added, are presented in Figure 3.

[5] Mogridge (1997, p.7) states that "we call the resulting hypothesis the Downs/Thomson hypothesis, namely that at equilibrium, the generalized costs of car and collective transport will be equal".

The curves that are depicted represent travel time functions –as a function of traffic– as capacity is increased. Squares and triangles show equilibrium generalized costs (after public transport is optimized) for each level of road capacity. The message is clear: successive road expansions decreases both generalized costs, because it allows to move people from a very congested transit system to cars, whose congestion is relieved by investments. The Figure also establishes that the public transport cost curve is, indeed, not downward sloping. Because of this, using a deterministic demand model does not restore the Downs-Thompson paradox as the intersection is between two upward-sloping curves.
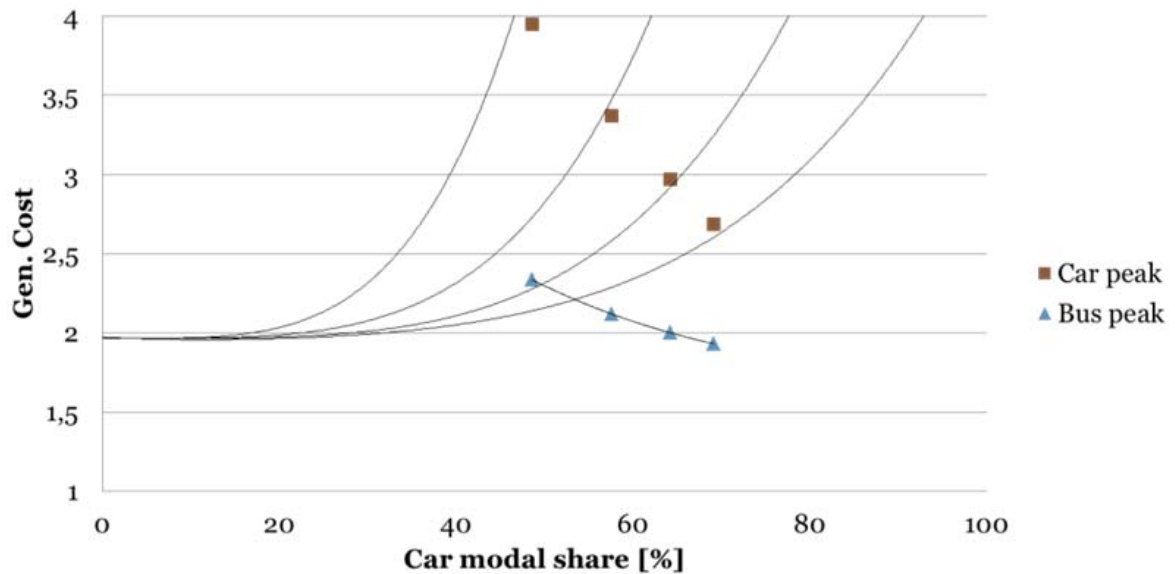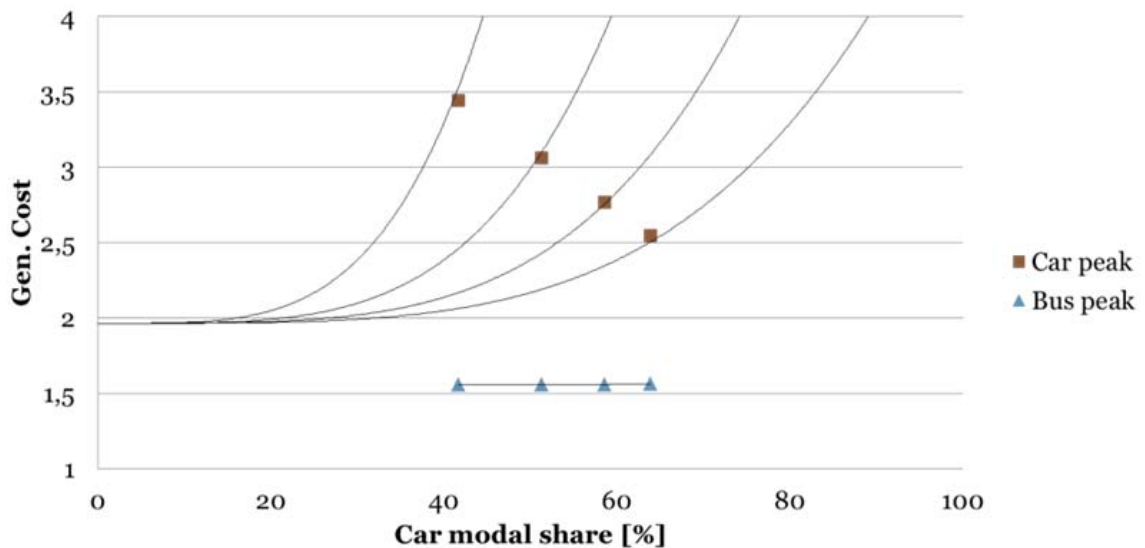

Generalized cost and modal split, peak-period and low-capacity bus stops. **Figure 3**

We then repeat the exercise considering the medium, high and infinite capacity bus stops. Results for the high capacity bus-stop are summarized in Figure 4. Again, one can see that car drivers are better off with the investments. Bus riders are, in this case slightly worse-off, but this is really marginal. Considering an infinite capacity at the bus stop, that is, that there is no congestion but a constant boarding time per passenger, does not affect the results. This means that (i) higher capacity at the bus stops allow for transit cost curves to be close to constant or slightly downward sloping rather than upward sloping yet, evidently, in the peak, the Mohring effect is simply exhausted (ii) the Downs-Thompson paradox is unlikely to hold in the peak if the demand model allows for differences in equilibrium generalized costs, as it is the case with most used mode choice models. Indeed, if we use a deterministic mode choice model together with high capacity bus stops, the Paradox revives, although the increase in generalized costs are quite minimal for both modes (about 0.01 increase). This confirms the conjecture of Basso and Jara-Díaz (2012) that the paradox hinged on the demand model.

We next look at what happens in the off-peak. There, the Mohring effect could have a larger impact since smaller total demands should depress transit frequencies, making it more likely that the paradox hold for, at least, bus riders. This is indeed the case as Figure 5 shows.

We performed a few sensitivity analyses: we fixed the spacing between bus stops rather than

optimizing every time and we diminished total demand by 30% and increased the free flow to consider a less congested initial situations. Our findings were not changed.

Generalized cost and modal split, peak-period and high-capacity bus stops. **Figure 4**
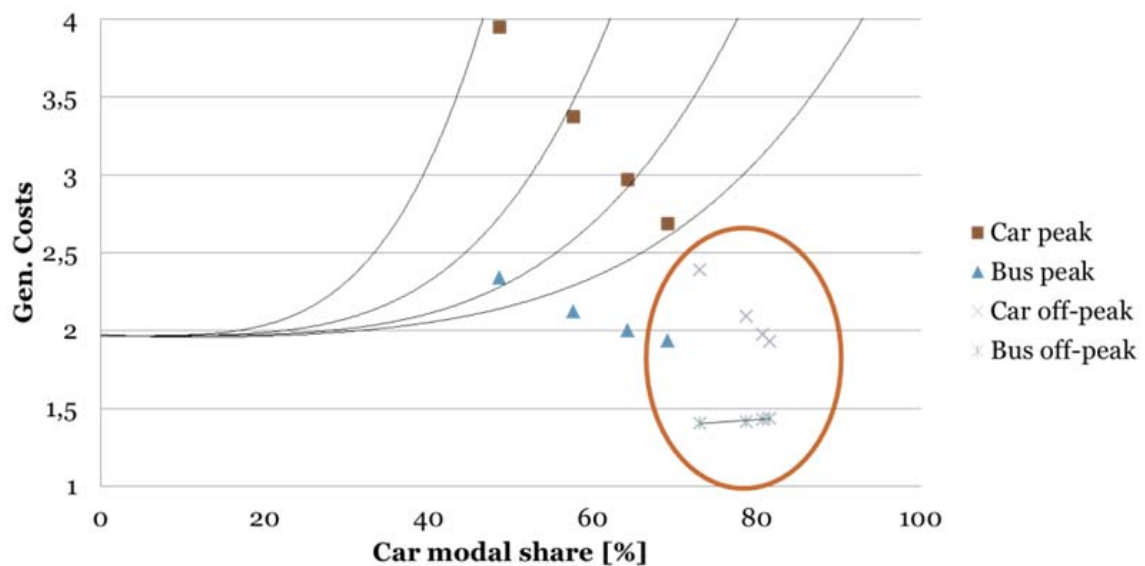
Generalized cost and modal split, off peak-period and high-capacity bus stops. **Figure 5**

We then analyze how results change if, both before and after the road expansion, optimal transit subsidies or optimal congestion pricing were in place, together with dedicated bus lanes. While the level of generalized cost changes, the conclusions does not: it is still true that with low capacity bus stops, both car drivers and bus riders are better off after the road expansions, while with high capacity bus stops, car drivers are better off while bus riders are slightly worse off due

to small decreases in (already high) frequencies.

When we consider mixed traffic conditions and no other policy, both car drivers and bus riders are always better off with road investment in the peak, irrespective of the capacity of the bus stop. What happens is that now the road expansion directly benefits the transit system by reducing congestion while buses are in motion. This effect dominates the small Mohring effect (depressed frequencies) that is present even if bus stops have high capacity. In the off-peak, under mixed traffic conditions we can still get that bus riders are worse off after investment; indeed, congestion on the road is not as important but the Mohring effect is. Adding congestion pricing works along the same lines: it leads to a less congested peak, making it possible again that, with high capacity bus stops, bus riders end up worse than before the road investment.

4. EFFICIENCY OF ROAD INVESTMENTS

The previous section showed that when considering more realistic demand models and bus stop operations, it is very likely that the Downs-Thomson paradox does not hold. At the most, only half of the paradox would: bus riders may end up slightly worse off after road investments, yet car drivers would always be better off. That analysis, however, looked only at generalized cost changes. But, indeed, the levels of generalized costs in each of the initial and final situations were different, hinting that the efficiency implications of road investment and the other policies are worthy of study. This is what we pursue in this section.

We again start with a low-capacity bus stop and a 3 lane road, and we compare the efficiency gains of four policies: (i) increase road capacity by one lane, (ii) keep capacity constant but subsidize 45% of bus operating costs, (iii) keep capacity constant but charge optimal car congestion pricing, (iv) keep capacity constant but devote one out of three lanes for exclusive transit traffic.

One of the key issues in this welfare analysis is that of costs, and one of the main problems here is that the cost of expanding the road network is something that varies dramatically according to specific conditions of each city. For example, to expand the road infrastructure, is it necessary for authorities to buy land? In many cases the Government will need to expropriate and that could be quite expensive depending the current use of that urban land. For example, without the need to seize any land, Dutch authorities suggest a cost of 0.2 €M/year-km highway lane while UK authorities suggest 0.6 $M/year-km for trunk road lane (Infrastructure cost review, UK, HM Treasury); but several EU cost-benefit analysis guidelines argue that those numbers could be five times higher if expropriations are needed.

We thus start by considering that no expropriations are needed and therefore use the cost suggested by the Infrastructure cost review (UK, HM Treasury). Figure 6 summarizes welfare results; detailed results for each relevant value (prices, speeds, modal and period shares) are available upon request. What figure 5 shows is that, given the situation we analyze, road expansion is the best stand-alone path welfare wise. Note that mixing subsidies, bus lanes and congestion pricing will not alter the results since Basso and Silva (2014) found little

complementarity between them.
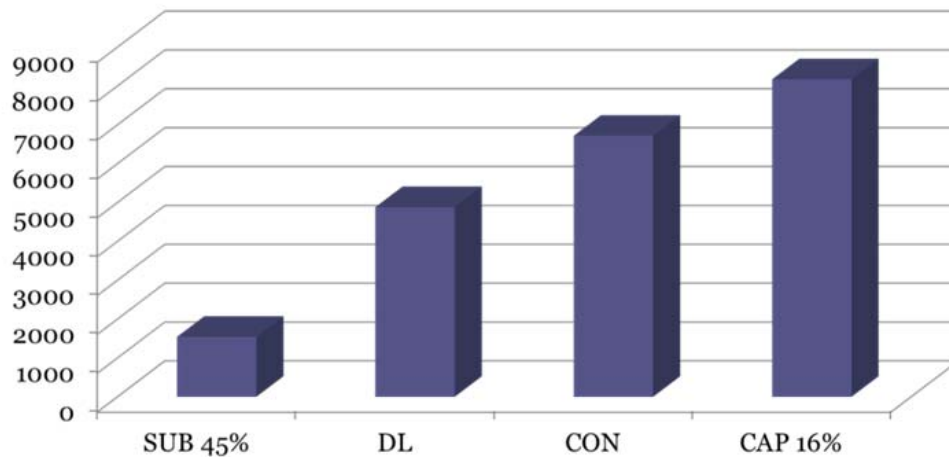
Welfare gains from the base case of transit subsidies, dedicated bus lanes, optimal congestion pricing and road expansion (one additional lane). **Figure 6**

In order to assess the importance of expropriation costs on the previous result, we compute *indifference amplifying factors*, that is, by how much should construction costs be multiplied by, to make road expansion as good as the other policies. Our results show that, if construction costs were 2.75 higher, expanding the road becomes as efficient as optimal congestion pricing. If construction costs were 4.95 times higher, the road expansion would be as efficient as bus lanes (and obviously, less efficient than congestion pricing. Finally, the indifference amplifying factor for subsidization is 8.96.

What we consider next is the efficiency of road expansions when any of the other three policies are in place so, for example, what we want to know is how efficient is to increase road capacity when bus lanes are in place, as compared to, for example, add capacity again (a fifth lane). Figure 7 summarize the results.

We first note that there is sizeable complementarity between capacity expansion and transit subsidization. That complementarity somewhat decays with bus lanes and congestion pricing. Yet, in all those three cases, the message is clear: there are sizeable welfare gains from expanding road capacity.

But additional insights can be gained if we suppose that the road was already expanded or that that the initial network was already larger. If we consider that four lanes were already available, the welfare gains from subsidization, bus lanes and congestion pricing are given by the first three green columns in Figure 7. The welfare gain of expanding (capacity) again is given by the difference between the last green column on the right and the last purple column on the right. What this shows is that expanding capacity further is now the least desirable policy. It is dominated by the other three being bus lanes the new best stand-alone policy. This speaks that capacity investments may be welfare improving under highly congested situations (and no or cheap expropriations) but, rapidly, management and pricing policies become the best strategies: with the additional fourth lane, the base situation has, in the peak, only 14 km/hr for buses and 18 km/hr for cars.
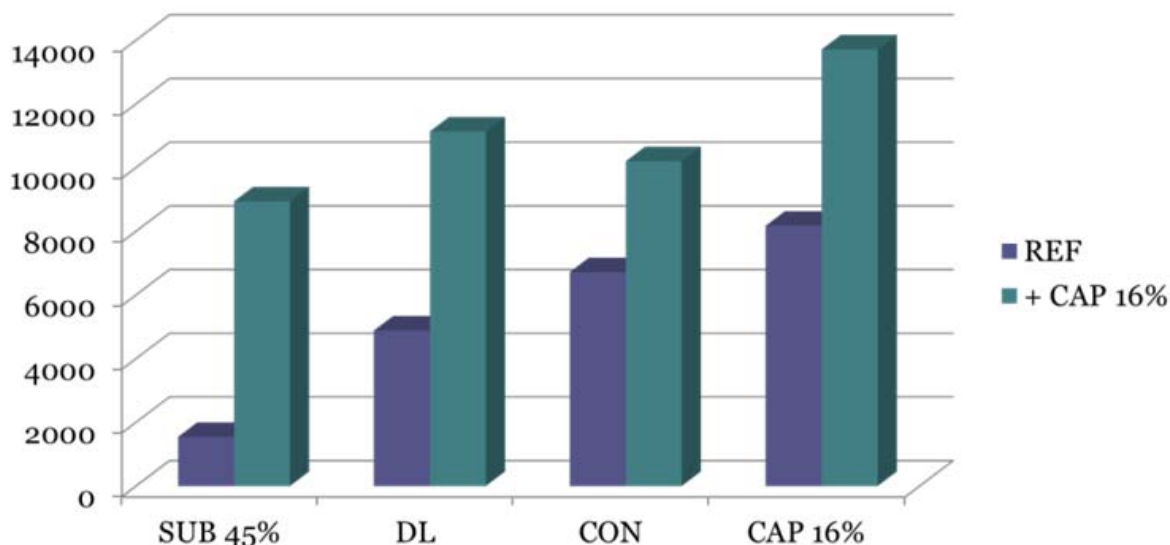
Road expansion and its interaction with other urban transport policies. **Figure 7**

We finally repeat all the analysis in this Section but considering better bus stop operations: the medium capacity case in which payment is through a magnetic card, bus stops have two berths, and boarding takes place only through the front door. Figure 8 summarizes the welfare results. Now, expanding road capacity from the base case (three lanes) is no longer the best alternative; congestion pricing and bus lanes dominate. Note that the initial situation was still very congested, with peak speeds of 12 km/hr for buses and 15 km/hr for cars. The message is very powerful: in a highly congested urban situation, the public transport system capacity, and particularly its bottleneck, the bus stops, are key. Improving these will then open the door to use management (bus lanes) and pricing (subsidies and congestion pricing) rather than large capacity expansions to manage congestion. Road expansion is something that, while being welfare improving, has a limited overall scope to be chosen in a strict cost-benefit analysis framework.
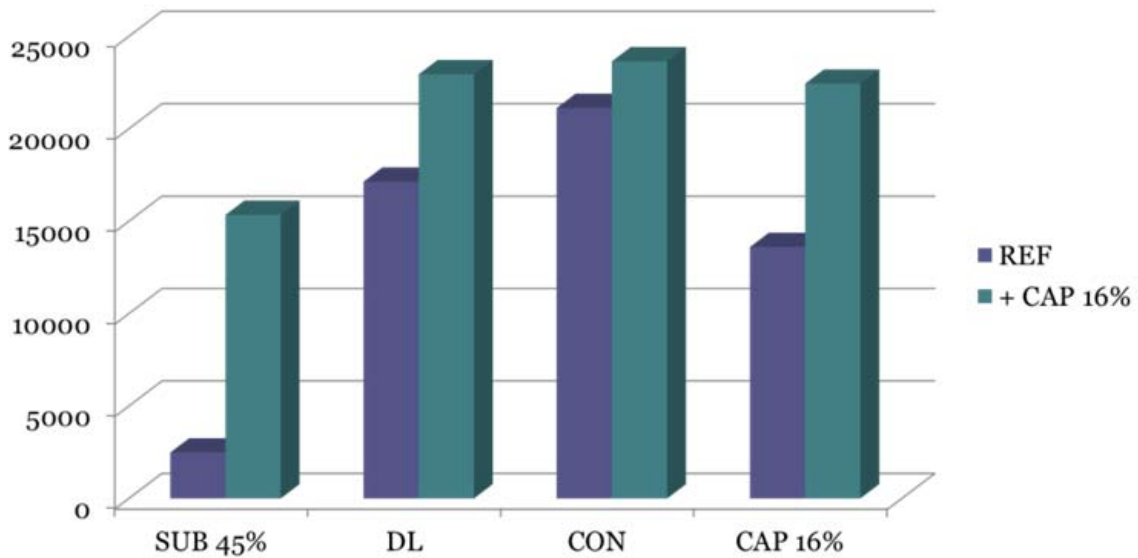
Welfare gains of urban transport policies with medium-capacity bus stops (no expropriations).
Figure 8

5. CONCLUSIONS

We have used a quite complete model of a bimodal system to study under which conditions the Downs-Thomson paradox holds and what are the welfare implications of following a rod capacity expansion path. The model features user heterogeneity, cross-congestion effects between cars and transit, intertemporal and total transport demand elasticities, and is simulated using data for London, UK.

We have shown that the Downs-Thomson paradox, in its most simple form, is not likely to hold when the mode choice model allows for generalized costs differences in equilibrium, as is the case with most of the models used in practice. In a nutshell, generalized costs did not increase in equilibrium after road expansion. We further showed the importance of realistically modeling bus stop operations: depending on the capacity of the bus stop, even bus riders may benefit from road capacity investments.

We then studied the efficiency of capacity expansions, comparing it to the welfare gains of other possible policies, namely, dedicated bus lanes, transit subsidies and congestion pricing. We found that, while road expansion is indeed welfare improving, it has a limited overall scope to be chosen in a strict cost-benefit analysis framework; it would only when congestion both for cars and buses is very strong, and when investment costs are low (probably because expropriation costs are). Our most important message is that in a highly congested urban situation, the public transport system capacity, and particularly its bottleneck, the bus stops, are key. Improving these opens the door to use management (bus lanes) and pricing (subsidies and congestion pricing) rather than large capacity expansions to manage congestion.

A more adventurous policy conclusion would be that when capacity is expanded, one should observe improvements, something that at a first glance would lend support to advocates of large urban infrastructure spending. Yet, from a welfare perspective, those investments would probably not be the best available policy. Needless to say, our results would benefit from a longer-run view; it may be the case that additional car traffic is indeed induced from sources other than the transit system.

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